A Mobility-Aware General-Purpose Vehicular Ad-Hoc Network Clustering Scheme

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Clustering is an effective method of topology control for wireless ad-hoc networks. Clusters introduce a structure in a flat network and can guarantee some basic levels of performance in presence of high mobility and large number of nodes. Therefore clusters can effectively increase the network capacity by the spatial reuse of network resources. Robust clustering schemes designed specifically for VANETs must address cluster stability and the high-mobility exhibited by the nodes, while reducing communication and computational costs. This paper presents a distributed multi-hop clustering scheme designed for VANETs, which utilizes mobility information to generate a stable cluster structure, maintained through the propagation of periodic DSRC safety messages. Our scheme takes the directionality of VANET nodes into consideration, where clusters are formed only between vehicles exhibiting a similar mobility pattern. Simulation results confirm that the execution of our scheme, due to its features, increases the average cluster lifetime and stability, and reduces the amount of communication and processing needed to form stable cluster structures in VANETs.

Keywords: VANET, distributed, mobility-aware, clustering, scheme

1. INTRODUCTION

Clustering is an important area of research for Vehicular Ad-Hoc Networks (VANETs), which has received much attention from the academic community in recent years ([3, 4, 6-9, 15, 16]). Unlike a non-clustered network, its counterpart can guarantee scalability and some basic levels of performance in presence of high mobility and large number of nodes. Clustering is an effective tool for topology control because it can introduce structure in a flat network, and thus effectively increase the network capacity by the spatial reuse of network resources. Additionally, by the introduction of cluster heads, routing of information is simplified both in the intra and inter cluster domains, and the network as a whole. The cluster heads form a backbone of the network and act as local managers to cluster members. This means that clustering provides a great structure for data dissemination [13], where information is propagated through the cluster heads, which in turn decide the relevance of that specific information for the local area in question. Finally, a regular node in a cluster structure needs to know high-resolution information only about its co-members, thus reducing the overall information stored locally at that node, compared to any node in a flat network.

The communication overhead of a proactive routing protocol in a flat network with n nodes is \(O(n^2)\) [14]. For large-scale networks, such as VANETs where the number of nodes in a local urban area could range from tens of thousands to hundreds of thousands,
such an overhead would render the network useless. Therefore, the introduction of a hierarchical structure is of great importance to the performance of VANETs, and clustering proves to be one such effective method of topology control. However, clustering is not overhead-free and creating and maintaining cluster structures within an ad-hoc network comes with additional communication and computational costs. Furthermore, some clustering schemes suffer from a ripple effect of re-clustering ([9, 13, 16]), which happens when clusters are re-built over the entire network due to a single cluster failure. Most clustering schemes employ an explicit message exchange between nodes, and in the case of high mobility (as in VANETs) cluster related information is exchanged more rapidly, causing higher bandwidth consumption and reduced network performance.

Depending on the approach taken for cluster formation/maintenance, clustering schemes are categorized as low or high-maintenance, mobility-aware, energy-efficient, load-balancing, or a combination-metrics-based, where any of the previous methods are combined. It is desirable for robust clustering schemes designed for VANETs to be low-cost and to employ mobility-awareness, while conforming to the properties of the network. Additionally, they must not make an assumption of a stationary period for cluster formation, and they must address cluster stability and the high-mobility exhibited by the nodes, while reducing communication and computational costs.

This paper presents a novel mobility-aware, General-purpose VANET Clustering scheme (GVC), which unlike existing schemes is tailored specifically for VANETs and conforms to the properties of the network. GVC forms general-purpose multi-hop clusters and aims to support operations such as data aggregation and dissemination, intelligent propagation of emergency warnings and road conditions, large distance routing, etc. Compared to existing work GVC exhibits the following properties and advantages:

- Our scheme takes the mobility of VANET nodes into consideration, where clusters in GVC are formed only between vehicles traveling on the same road and in the same direction, thus increasing the average cluster lifetime and stability.
- Due to the previous property, our scheme provides robust operation in the cluster formation and maintenance phases and reduces the amount of communication and processing needed to form stable cluster structures, thus increasing the overall network performance.
- GVC is a distributed scheme that runs asynchronously and concurrently on every VANET node and requires for cluster state information to be exchanged between nodes periodically. GVC utilizes the periodic safety message propagation of Direct Short Radio Communication (DSRC), to piggyback the cluster state information, and maintain the cluster structure. The guaranteed small interval of DSRC message periodicity [17], assures that GVC clusters are stable and constructed quickly.

The rest of the paper is organized as follows. Section 2 reviews related work in the area of research. Section 3 presents the details of the GVC scheme. Section 4 describes the simulation setup and results. Section 5 concludes this paper.

2. RELATED WORK

VANETs inherently possess a mobility element that is very different from any other
type of network, which may present an obstacle or advantage in the design of protocols and communication schemes. The Mobility Based Metric for Clustering in MANETs (MOBIC) [9] is a clustering scheme that takes mobility into consideration. MOBIC is a scheme which is designed with somewhat uniform group mobility in mind, where nodes are expected to move with low relative speeds to each other, similarly to vehicles on a highway. The cluster creation and joining methods in MOBIC are similar to those of the Distributed Dynamic Clustering Algorithm (DDCA), a well-known MANET dynamic clustering scheme. The difference is that any nodes that possesses a low relative speed to its neighbors, calculated by taking into account the signal strength of a pair of messages from each neighbor, has the ability to become a CH. A node becomes a CH if it has the lowest relative speed to all the nodes interested in being cluster members. This operation requires a lot of pairwise communication before the decision is made which node to become the CH. A unique feature of MOBIC that avoids unnecessary cluster merging is that merging occurs only when a CH is within 1-hop communicating range of another CH that is only moving in the same direction. The performance of MOBIC can decrease rapidly in the event of random node movement and highly-variable node speeds. In cases such as these, cluster stability is not guaranteed by MOBIC, but could be enhanced by modifying its 1-hop cluster size property, as our scheme does. Our GVC scheme extends the 1-hop requirement of MOBIC, and behaves similarly to MOBIC in the areas of cluster formation and merging, but does not impose the speed relativity requirement. By not imposing a hop-limit to the cluster structure, GVC allows for clusters to span a larger physical area. This ensures that the cluster reach can be extended in sparsely populated (rural) roadways and areas, which enhances inter-cluster connectivity and is also important for safety applications.

MOBIC is based on the low-cost cluster creation and maintenance principles defined by the Least Cluster Change (LCC) [16], and the Passive Clustering (PC) scheme [13]. LCC requires an initial stationary period for cluster construction. The scheme is a pioneer in building robust cluster structures based on looser rules than its predecessors, which preferred to execute re-clustering procedures periodically to maintain cluster stability. LCC forms initial clusters by simply choosing CHs to be the nodes with the lowest ID in the neighborhood. This property of LCC increases the overall clusters’ stability and their lifetime. Re-clustering in LCC is done only in two possible cases: when two CHs are within 1-hop communication range (causing a cluster merge), and when a node cannot access a CH (forcing it to create a lone cluster). The latter case of re-clustering in LCC may be a cause of large communication overhead in the network in the event that there are frequent CH disconnects in the cluster architecture. Unlike LCC, our GVC scheme does not create lone cluster structures, thus avoiding the related overhead.

The PC scheme does not require a stationary period for initial cluster formation and nodes do not exchange cluster control messages explicitly. Cluster control messages in PC are piggybacked on ordinary messages that are exchanged only when nodes have something to send. Our scheme behaves similarly to PC in this sense, by including clustering information in the DSRC periodic safety message broadcasts. Not every node that can be a gateway becomes one in PC. The number of gateways in the network is limited by a rule which states that the distance between gateways and CHs must be above/below some (unspecified) threshold value. This decision requires a global knowledge of the cluster structure within the network and may be the cause of unnecessary delays or over-
head. Our GVC scheme improves on PC by not requiring global knowledge for gateway selection.

The Cluster-Based Multi-Channel Communication Protocols in VANETs (CBMCCP) [5] focuses on the division and usage of DSRC dedicated channels for inter and intra-cluster purposes, assuming a simplified clustering scheme and it consists of three protocols: cluster configuration, inter-cluster communication, and coordination and communication protocol. The scheme allots two of the seven available DSRC channels for inter-cluster control and data accordingly. One channel is allotted for intra-cluster control and the remaining four channels are allotted for intra-cluster data communication. CBMCCP does not discuss the methods of creating clusters, rather it assumes clusters already exist and a vehicle that enters highway initiates a join cluster routine. Cluster heads election is initiated in the event of a failure of a CH. The intra-cluster coordination and communication protocol focuses on dividing intra-cluster resources using a TDMA based scheme. Inter-cluster communication is done via different channels and differing priorities depending if the type of traffic is real-time or non-real-time.

The stable clustering in pseudo-linear highly mobile ad hoc networks [1] presents several solutions such as the Dynamic Doppler Velocity Clustering (DDVC) and the Dynamic Link Duration Clustering (DLDC). The schemes consider only 1-hop clusters, aiming to provide a stable clustering scheme for highly mobile nodes with pseudo-linear directionality, such as vehicles on a highway, trains, commercial air traffic, etc. DDVC provides a mobility metric which could be utilized for cluster creation in cases when GPS data is unavailable for positioning information. The algorithm specifies a metric derived from the relative velocity between nodes, by examining the Doppler shift of the control packets exchanged. From this metric DDVC determines, similarly to MOBIC, the directionality of moving nodes, and creates clusters based on the information. DLDC is an additional clustering scheme which creates clusters based on the estimated link expiration time between nodes. When position and velocity are taken into consideration, the link duration time between two nodes can be more precisely estimated, and this estimation is utilized by DLDC to create clusters that more stable.

The Cluster-Based Multichannel MAC Protocols (CMCS/CMMP) defined in [2] are suited for QoS provisioning over VANETs. Even though CMCS focuses on the MAC specifics and methods for providing QoS, it defines a clustering scheme based on three different protocols: the Cluster Configuration Protocol, the Intercluster Communication Protocol, and the Intracluster Coordination and Communication Protocol. The scheme effectively manages cluster-membership, real-time traffic delivery and non-real-time data communications. The commonality between CMCS and DDVC, as well as our proposed scheme GVC, is that clusters are only formed between nodes moving in the same direction, therefore providing a solid base for performance comparisons.

3. THE GVC SCHEME

This section begins by stating the network model and assumptions taken into consideration for the design of GVC, followed by a detailed description of the mode of operation and a mathematical model of the scheme.
3.1 Network Model

All the nodes in the network are vehicles equipped with an on-board communication system based on the DSRC service standard, with a transmission range between 300 m and 1000 m. The MAC protocol is assumed to be 802.11a based, as per ITS industry standards, with a Carrier Sense Multiple Access (CSMA) capability allowing for the avoidance of collisions, and the wireless channel is assumed to be error free. The GVC scheme is not dependent on GPS, because it could extract vehicle directionality similarly to MOBIC; however the communication system in each vehicle may coordinate with a GPS device, which can provide positioning, velocity, and global time information.

The network comprises \( N \) homogeneous vehicle nodes that are uniformly distributed in a two-dimensional Euclidean space, with vehicle positioning and mobility constrained to predefined highway paths. The network dynamics is bounded by a realistic VANET mobility algorithm, the freeway mobility model. The model assumes that the flow of traffic is continuous without impedance due to collisions and other obstacles. Individual vehicles’ speed exhibit low variance compared to the speed limit of the highway they are traveling on. Additionally, it is assumed that cluster formation is not for any specific application, (such as platooning for example) rather clusters are created for general-purpose support such as data aggregation and forwarding, and enhanced large distance routing.

3.2 GVC Modus Operandi

The GVC scheme operation is next described in four distinct phases of operation: starting with the initial cluster formation, where all nodes within the network are assumed to have just powered on; the cluster maintenance phase, where clusters are in a stable state; cluster merging, where two or more clusters satisfy the merging requirement set by GVC; and the CH handoff phase, which happens when a CH intends to leave its cluster.

3.2.1 Initial cluster formation

Fig. 1 depicts the finite state machine dictating the state of any GVC node. GVC does not assume a stationary period for initial cluster creation. Nodes that power up immediately enter the Lone state, in which they broadcast periodically. The DSRC standard states that periodic safety messages are broadcasted by nodes at least every 100 ms and at most every 300 ms via the DSRC control channel [18]. Furthermore, non-safety periodic messages in DSRC can occur at minimum of 50 ms, depending on the types of applications that are running in a given VANET. This means that GVC can utilize any of the DSRC periodic messages as messages where any given node can learn about its immediate one-hop neighborhood within a maximum time-frame of 300 ms. The GVC clustering related information could be piggybacked onto these DSRC periodic messages, thus avoiding the explicit forwarding of GVC messages. If a given node does not hear from any other nodes, it will remain in the Lone state. If it receives at least one message that has a time-stamp lower than its own last sent message, and it is from a node moving in the same direction, the node in question will switch its state to being a Member of a
cluster in the process of formation. Then that node will send a “Join” message to the node which sent the lowest time-stamped periodic message (the potential CH), thus informing it that it wishes to become a member of the cluster. Once the potential CH receives the Join message it will then switch its state to CH. This sequencing of events guarantees that the node which is first to broadcast a message eventually becomes a CH.

In a flat MANET, the criterion for a node becoming a gateway (GW) is not usually related to a directionality factor. For VANETs the idea is that if two clusters are moving in opposite direction on the same highway, and if the front most nodes of the clusters can hear each others, then those two nodes do not satisfy the criterion to be GW, since as time passes by eventually every node within the cluster will get to hear every node of the other cluster. In this case if every potential GW node reported to its CH that it is in direct communication with another CH, the intra-cluster overhead would increase drastically. Therefore, a good gateway is defined to be one which is in direct communication range with other nodes from another cluster that is moving in the same direction on the same highway. This does not mean that two oppositely moving clusters cannot exchange information, rather the assignment of quasi-permanent GWs is dismissed for the cause of better inter-cluster performance. Safety messages, for example, that are sent by other clusters will propagate throughout the clusters via these potential GWs anyway, because they are broadcasted with \(1 - p\) persistence.

A potential GW node becomes a GW in a similar fashion as the CH is elected in the initiation phase. Assuming that several nodes satisfy the good GW criterion, the one which is the first to broadcast this information intended for its CH will become the GW. Under the network assumptions stated in 3.1, this will result in each cluster having exactly two GWs, one in the front and one in the back. In a flat MANET, it could be possible that a cluster may have two gateways for any other cluster within its range. In fact, for a fully connected MANET with \(X\) clusters, the number of GWs pairs (Grange) could range from: \(X - 1 \leq Grange \leq \left(\frac{X}{2}\right)\), while in GVC, under normal conditions the number of GWs is fixed to \(X - 1\) pairs per direction of a highway.

### 3.2.2 Cluster maintenance

The cluster structure is kept firm through the periodic messages propagating throughout the group. In multi-hop clusters, each node will forward the periodic message from
the CH to the edges of the cluster, informing the members that they are still connected to their CH. The reverse operation is done also through periodic messages, where the information is aggregated from the edges of the cluster towards the center. The following are the operations comprising the cluster maintenance phase.

A Gateway could possibly move out of range of the node(s) it is connected to from the neighboring cluster, or it could lose connectivity with its own CH. In the first case, the GW will send a message to the CH informing it that it is no longer fit to be a GW and the node will revert back to the Member state. In the second case, no explicit messages are sent to the CH. The cluster head will find out that the connectivity with its GW has been broken through the periodically aggregated reverse messages.

3.2.3 Merging of clusters

In the case of two CHs being in direct communication range (relative to the number of hops requirement) a merging procedure is executed, where explicit merging messages are exchanged between the CHs. In a VANET this would occur when the two clusters are asymmetrical and happen to collide with each other. GVC employs absorption merging, where the cluster with more members will take-in the smaller cluster’s members. One explicit message from each CH is required to be sent to the other CH informing it of its size, and once the smaller one is determined it has to send the details of its member population to the new CH. The members of the absorbed cluster will learn of the absorption through the next round of periodic messages sent by the new CH. The nodes on the outer edge of the absorbed cluster that no longer satisfy the hop requirement to be members of the new cluster will revert to the Lone state.

There are two possible actions in the event when a CH learns that the connection to its members has been broken. The first is if there is still a connection to any of its members through another node, the CH will handoff the responsibility to the most connected node within the cluster, and the second if there are more two or more possibilities with equal connectivity it will make a random decision of which node to be the new CH. The new CH will keep the cluster ID and the cluster members will be informed of the handoff in the next periodic update. If the CH has no way of communicating with its members, they will again learn about the disconnection in the following update period, and all (including the departing CH) will revert to the Lone state, forcing a cluster initialization, or joining another nearby cluster.

3.3 GVC Performance Analysis

At the initial time \( t = 0 \), there are \( N \) nodes in the network. At any given time \( t \), the distribution function describing the number of nodes that emit a periodic message could be represented by the following function:

\[
f(t - t_i) = \begin{cases} 
1 & \text{if } t - t_i = \frac{t}{\Delta t} t_p \\
0 & \text{otherwise}
\end{cases}
\]  

where \( t_i \) is a random initial time it takes for a node to transmit a periodic message, \( t_p \) is
the time of periodic message broadcasts, and $\Delta t$ is the smallest increment in time. Thus, at time $t$, the number of nodes sending a periodic message is equal to $M = \sum_{i=1}^{N} f(t-t_i)$, where $M \leq N$, which is also the total number of messages sent. On the other hand, the probability that $M$ nodes receive a join message from the remaining set of $N - M$ nodes at a given future time, as a function of distance, is:

$$f(r-d_{ij}) = \begin{cases} 1 & \text{if } r-d_{ij} > 0 \\ 0 & \text{if } r-d_{ij} \leq 0 \end{cases} = H(r-d_{ij})$$ (2)

where $H(r-d_{ij})$ is the Heaviside step function, $d_{ij}$ is the distance between the $i$th and $j$th node, and $r$ is the communication radius. Following, the total number of received Join messages by $M$ nodes is: $M_r = \sum_{i=1}^{M} \sum_{j=1}^{N-M} H(r-d_{ij})$, and the total number of exchanged messages, such that $M$ nodes can either form or join a cluster is:

$$M_{\text{total}} = M_s + M_r = \sum_{i=1}^{N} f(t-t_i) + \sum_{i=1}^{M} \sum_{j=1}^{N-M} H(r-d_{ij}).$$ (3)

From this, the number of messages exchanged per node for the purpose of creating or joining a cluster is

$$M_{\text{a}}(d_{ij}, t) = \frac{M_{\text{total}}}{M} = 1 + \frac{1}{\sum_{i=1}^{M} \sum_{j=1}^{N-M} H(r-d_{ij})} \sum_{i=1}^{N} f(t-t_i).$$ (4)

We can further refine our analysis by incorporating a stochastic process for the arrival of periodic messages within the model. Given that the arrival rate of the periodic messages is a Poisson process with an arrival rate of $\lambda$, the number of nodes sending a periodic message at time $t$ could be modeled by the following equation:

$$M(t) = N f(M, \lambda t) = \lambda t \frac{e^{-\lambda t}(\lambda t)^M}{M!} = \frac{e^{-\lambda t}(\lambda t)^{M+1}}{M!}.$$ (5)

Introducing the process to Eq. (2) and substituting the value in Eq. (3), we get the following quantity:

$$M_{\text{total}} = M(t) + M_r = \frac{e^{-\lambda t}(\lambda t)^{M+1}}{M!} + \sum_{i=1}^{M} \sum_{j=1}^{N-M} H(r-d_{ij}).$$ (6)

which defines the total number of relevant messages exchanged in the network for the purposes of forming or joining a cluster. Expressing Eq. (6) in per-node terms we derive
which provides us with a quantity to evaluate the load on each node in the network.

The total number of messages exchanged for the formation of GVC clusters could be represented based on the values of the system/simulation parameters such as the communication radius $r$, and the vehicle density $\rho$. Assuming that the initial time $t_i$ is the same for all the nodes, then the total number of initially sent periodic messages $M$ would be equal to the total number of nodes $N$ according to Eq. (1), or by Eq. (6): $M = \lambda t f(M, \lambda t)$. The number of nodes in communication range of the potential CH, i.e., the number of nodes per cluster, can be estimated as a product of the vehicle density and communication radius according to Eq. (2) as $N_{\text{cluster}} = \rho r + 1$. This implies that the expected number of clusters is

$$C = \frac{M}{N_{\text{cluster}}} = \frac{M}{\rho r + 1}$$

(8)

Therefore, the estimated number of join request messages in the network is $C \cdot (N_{\text{cluster}} - 1)$, the number of nodes within each cluster sending a join request excluding the CH, or

$$M_{\text{req}} = \frac{M}{\rho r} (\rho r - 1).$$

(9)

Introducing Eq. (9) into Eq. (7) gives us the total number of exchanged messages for the purpose of forming clusters, as a function of the communication radius $r$:

$$M_{\text{total}} = M + \frac{M}{\rho r} (\rho r - 1) = 2M - \frac{M}{\rho r} = \frac{2M \rho r}{\rho r + 1}.$$

(10)

(a) Cluster size as a function of the node density.

(b) Cluster size as a function of the node preferred speed.

Fig. 2. Model of the average cluster size.

Eq. (9) can give us an estimate of the average cluster size, as a function of the density, as shown in Fig. 2 (a), where the density is expressed in terms of the vehicle arrival rate $\rho = \frac{1}{\lambda}$ and $V$ is the average proffered node speed. The model shows that as the density increases, the expected size of the clusters increases in a linear fashion. Fig. 2 (b) shows the expected cluster size of the model as a function of the preferred node speed in
low (GVCld), medium (GVCmd), and high (GVCdh) density scenarios. The average cluster size drops off rapidly as the preferred node speed increases. This is due to the higher dynamics within the system, where because of their speeds nodes spend less time participating in a single cluster formation.

4. SIMULATION RESULTS AND ANALYSIS

In this section we compare the presented model to the results obtained from simulating the operation of the GVC scheme. We simulated a VANET according to the network model and assumptions stated in section 3.1. For each simulation we examine the first 300s of simulation time, and each data point represents an average of 10 simulation runs. The communication radius of the nodes was varied in increments of 100m in the DSRC specified radio range. Vehicles were simulated to travel on a 5 km long four-lane road (two lanes per direction), with an initial speed between 18m/s to 22m/s. The vehicle density was represented as a function of the vehicle generation rate $\lambda$ (where $\rho = \frac{\lambda}{\lambda}$), which was varied from 0.1 vehicles/s (vps) to 0.5 vps in increments of 0.1 vps. The hop limit was set to one, for most simulation runs.

Fig. 3 (a) shows that the average number of clusters created by GVC conforms to the theoretically predicted pattern, calculated by plugging in the simulation parameters in Eq. (9), and that it follows the lower bound very closely. As the communication radius ($r$) increases it can be seen that the number of clusters created, per each of the five densities investigated, falls off and converges quickly. This result was expected, since as $r$ grows, the more vehicles should be within communication range of existing clusters, and the need to create a new one diminishes. The average cluster size, depicted in Fig. 3 (b), shows that as $r$ increases the number of members per cluster increases also. The simulation results of GVC exhibit a positive trend in following the theoretical model, especially in the cases of higher vehicle densities, when $\lambda = 0.4$ and $\lambda = 0.5$. In the lower density ranges, the cluster size seems to taper off at some point even as $r$ increases. This result is due to the relatively sparser distribution of vehicles, which results in lower overall connectivity, and lower probability for GVC to form larger clusters.

Fig. 3. GVC characteristics.
Fig. 4 (a) illustrates that the average lifetime of GVC clusters is proportionally dependent both on \( r \) and \( \lambda \). GVC clusters exhibit a relatively high longevity even in the lowest density and communication range, especially considering that this average includes short-lived clusters created due to the distribution and mobility of the nodes within the simulation. There is a significant lifetime gain as \( r \) increases, which is in the range of 30s. Vehicle density seems to also positively affect the average lifetime, but not as drastically as the communication range. The vehicle reaffiliation rate, shown in Fig. 4 (b) as an indicator of cluster stability, is a measure which shows the number of nodes per second that had to reaffiliate with another cluster due to cluster merges or failures. In GVC, this number increases slowly as \( r \) and \( \lambda \) increase, which is expected because when \( r \) and \( \lambda \) are large, the average cluster size is larger, and when a merge or failure occurs more nodes are affected. The figure also shows the effect of ignoring the directionality factor of moving nodes for cluster creation and maintenance. The vehicle reaffiliation rate in the sample of ignoring directionality, where \( \lambda = 0.3 \text{vps} \), is much (3 to 5 times) higher than the average reaffiliation rate exhibited by GVC. This also shows that GVC increases the stability of clusters while reducing communication for the purposes of cluster creation and maintenance.

The effects of varying the hop-limit are shown in Fig. 5. Fig. 5 (a) shows the positive effects of increasing the cluster hop-limit, where it can be seen that as we increase the hop-limit the average number of clusters created approaches the theoretically defined lower bound rapidly, but with a diminishing return. This result is expected, since as we increase the hop-limit, the size of the clusters increases also. Therefore there is a lower probability for new clusters to be formed, resulting in decreased overall cluster creation messages in the network. As expected, Fig. 5 (b) shows that the average members per cluster increases as we increase the hop-limit, thus increasing the inter-cluster maintenance communication and consequently the potential overhead. The results, again, follow the theoretical model closely, and follow a similar pattern as observed in Fig. 3 (b).

The following figures compare our GVC scheme with the related work. First, in Fig. 6 (a), we compare the average cluster size as a function of the average preferred node speed of GVC and CMCS, in varying densities. Fig. 2 (b) shows the expected behavior of
(a) Average number of clusters.
(b) Average cluster size.
Fig. 5. The effects of varying the hop limit.

(a) Average cluster size as a function of the preferred node speed.
(b) Average cluster size as a function of the node density.
Fig. 6. GVC performance comparison.

(a) Average cluster lifetime as a function of the preferred node speed.
(b) Node reaffiliation rate.
Fig. 7. GVC stability comparison.
GVC and Fig. 6 (a) shows the actual behavior of GVC as well as the behavior of CMCS. From this figure, it could be seen that GVC follows the theoretical model closely, yet the actual cluster size is a bit smaller than the expected. This figure also shows that in general GVC forms clusters of relatively smaller size than CMCS, which consequently results smaller and more compact clusters which exhibit a better lifetime than those of CMCS, as shown later in Fig. 7 (a). Fig. 6 (b) shows the performance of GVC in terms of the average cluster size as a function of the node density compared to MOBIC, LCC, DDVC and DLDC. From this figure it can be seen that the GVC cluster size follows the theoretical model’s predicted cluster size very closely, referring back to Fig. 2 (a). Also when compared to the other clustering schemes, GVC seems to be relatively unresponsive to the fluctuations in node density. This means that GVC clusters are smaller and more stable because of the way clusters are created in GVC, where the increase in density does not necessarily steeply affect the increase in cluster size.

Fig. 7 (a) illustrates the effect of the, previously observed, smaller GVC cluster size on the lifetime of the clusters. From this figure it can be seen that as the preferred speed of the nodes increases, the lifetime of both GVC and CMCS clusters degrades, yet GVC exhibits longer average lifetime in varied densities. Fig. 7 (b) shows the stability of GVC clusters as a function of the communication radius compared to MOBIC, LCC, DDVC, and DLDC. The figure shows that the node re-affiliation rate for GVC if far lower than those of the competition. The rest of the schemes have a tendency to reduce their re-affiliation rate as the communication radius increases, which is due to the fact that clusters contain more and more members. The end effect is that their cluster stability is relatively increased. GVC outperforms the competition by maintaining a relatively low re-affiliation rate, and consequently high cluster stability, in all of the examined communication ranges.

5. CONCLUSIONS

This paper presented a novel mobility-aware, general-purpose clustering scheme designed for VANETs, which takes the directionality of moving vehicles into consideration during the cluster creation and maintenance phases. The simulation results show that our GVC scheme creates robust cluster structures, which adhere closely to the lower-bound limits calculated by our theoretical performance model. GVC clusters exhibit a relatively long lifetime, even in scenarios with low vehicle densities and reduced communication radius. The GVC cluster structure is also very stable, especially if compared to when directionality is ignored. Due to this property the overhead associated with the clustering scheme is greatly reduced. Additionally, if all GVC-related data was to be piggybacked onto DSRC periodic safety messages, then the only cost associated with the operation of the scheme would be computational.

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