# A Position-Based Clustering Technique for Ad Hoc Intervehicle Communication

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***Abstract*—Intervehicle communication is a key technique of intelligent transport systems. Recently, ad hoc networking in the vehicular environment was investigated intensively. This paper proposes a new clustering technique for large multihop vehicular ad hoc networks. The cluster structure is determined by the geographic position of nodes and the priorities associated with the vehicle traffic information. Each cluster elects one node as its cluster head. The cluster size is controlled by a predefined maximum distance between a cluster head and its members. Clusters are independently controlled and dynamically reconfigured as nodes move. This paper presents the stability of the proposed cluster structure, and communication overhead for maintaining the structure and connectivity in an application context. The simulation is performed with comparative studies using CORSIM and NS-2 simulators.**

***Index Terms*—Ad hoc wireless network, cluster, intelligent transportation, sensor network, vehicular network.**

## I. Introduction

INTERVEHICLE communication is one of the four key systems defined in intelligent transportation system architecture [23]. The intervehicle communication enables each driver or each vehicle to communicate with other vehicles at any location at any time. Vehicles equipped with wireless communication devices are no longer isolated systems, and can instantly form vehicular ad hoc networks (VANETs) [9], [13], [15], [16], [18], [21]. Two passing vehicles can exchange data (single hop), or data can pass several other vehicles when they act as routers/relays (multihop) [20]. With this principle, highly efficient accident warning systems are possible; cars involved in an accident can send warning messages back over a predefined number of other vehicles, thus avoiding motorway pileups and enhancing the traffic safety. VANETs extend the horizon of drivers and automated systems in that the intervehicle communication not only helps the driver acquire real-time traffic information and react quickly, but also facilitates smooth driving according to varying transportation conditions. For example, drivers can change their route plan in case of traffic pileup, and also their vehicles can adjust the fuel economy, brake systems, or air-conditioning status based on the current traffic condition. Therefore, the safety and efficiency of the road traffic are improved.

However, VANET is fundamentally different from a typical mobile ad hoc network (MANET) with respect to the dominating models in MANET research [3], [5], [22]. Driver behavior, constraints on mobility, and high speeds contribute unique characteristics in VANET. In particular, [3] quantifies these differences as rapid topology changes, frequent fragmentation, small effective network diameters, and limited redundancy. Due to the relative speeds of vehicles, the topology of VANET keeps rapidly changing even though the movement of vehicles is somewhat predictable, i.e., they must stay on the roadway and have the same moving direction. A message path can typically survive 1 min while maintaining a transmission range of 500 m [9], [18]. Consequently, a VANET may suffer frequent partition, and hence, costly overheads for exchanging new topology information and reconfiguring each node [19]. Aoki and Fuji [3] also show that a typical effective network diameter is no larger than 9 hops. Moreover, limited temporal redundancy of roadways discourages the application of some routing protocols, which require multiple paths.

Traditional topology management approaches are not designed for the earlier vehicular environment. For example, energy efficiency for regular MANET is a critical issue but not for VANET, since vehicles are capable of recharging battery during their journey. More importantly, vehicle mobility related to transportation information should be considered together with communication issues. Based on the previous observation, we propose position-based prioritized clustering (PPC), a new topology control method for VANET. This proposal incorporates position information into a novel hierarchical clustering technique. In order to justify this proposal, a microscopic vehicle traffic simulator, CORSIM, is deployed along with NS-2, a widely used computer network simulator, to derive the results and conclusions.

The rest of the paper is organized as follows. Section II describes the PPC approach. Section III analyzes the stability of cluster and the needed communication overhead using a probabilistic model. Section IV shows the performance using simulations. Section V summarizes the paper and its key contributions to enable intelligent transportation.

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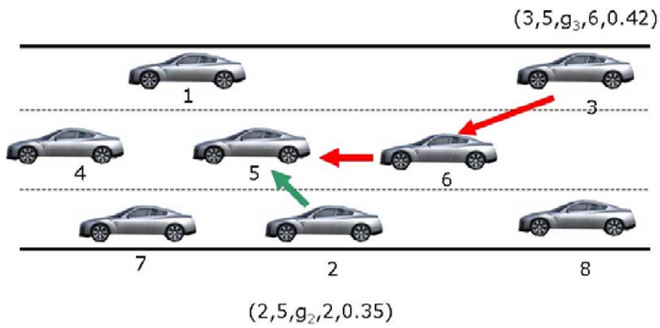


Fig. 1. Example of clustering vehicles disseminating cluster information.

## II. Position-Based Prioritized Clustering Technique

### A. Overview and Assumption

Clustering is a technique to group nodes in a network into logically separated entities called clusters. Clustering can simplify such essential functions as routing, bandwidth allocation, and channel access. Several heuristic clustering techniques have been proposed to choose cluster heads in an ad hoc network. These are lowest ID, highest degree, and node-weight heuristics [1], [5], [7]. However, they cannot be deployed directly in ad hoc vehicular networks, since their design objectives are not for high-mobility vehicular networks. For example, vehicles leave and enter highways randomly and rapidly, the computation task, then, causes a huge amount of communication overheads for each node to perform the heuristic technique based on the highest-degree algorithm. Cluster heads may frequently change their relative position on highways, and then, the size and stability of clusters change unpredictably if lowest ID and node-weight heuristics are used. On the other hand, vehicles on (one way) highways have almost the same direction within a certain area. Therefore, their geographical location and velocity information are helpful when they are evenly divided into nonoverlapping clusters along highways. [14] demonstrated that better performance could be achieved if the geographic position of the network nodes is known.

This work assumes that each node is assigned a distinct ID, which is greater than zero. For the clustering purpose, each node maintains a small amount of information of itself and its neighboring nodes. Periodically, a node broadcasts the information, which is referred to as its cluster information denoted by a 5-tuple ($i$, $h$, $g$, $i_N$, $p$), where

$i$: node ID;
$h$: cluster head ID;
$g$: node geographic location;
$i_N$: ID of the next node along the path from the node to its cluster head;
$p$: node priority.

Fig. 1 is an example network of clustering vehicles. Node 5 is the cluster head node and node 3 distributes its cluster message to its neighboring nodes. The meaning of cluster information is defined earlier; for example, $(3, 5, g_3, 6, 0.42)$ means that node 3 is using node 5 as its cluster head, and its geographic location is $g_3$, which is obtained from a GPS device, its next hop to the cluster head is node 6, and its priority is 0.42.

### B. Cluster Size and Minimal Dominating Set

The major objective of clustering is to achieve relatively stable cluster structure, because frequent cluster reconfiguration generates tremendous communication load, which significantly reduces available bandwidth for message dissemination. Effective cluster size is both related to radio transmission range and vehicle traffic density. Therefore, cluster size may limit radio efficiency and throughput. The density is time varying [4], [17]. Hence, the cluster radius $L$ is defined in this paper, in order to organize the nodes into a cluster within the given maximum distance. When a node moves relatively away from its cluster head, and the distance between the node and its cluster head is larger than the cluster radius $L$, it joins a new cluster if it can find an existing cluster head within $L$; otherwise, a new cluster is formed with the node as the cluster head. When the distance between two cluster heads is detected to be less than or equal to a predetermined threshold, $D(D \leq L)$, the cluster with less members is dismissed. Each of the nodes in the dismissed cluster finds a new cluster to join. This paper will investigate the impact of transmission range and traffic parameter on $L$ and $D$.

The topology of VANET is represented by an undirected graph $G = (V, E)$, where $V$ is a set of network nodes and $E \subseteq V \times V$ is a set of links between nodes. The minimum dominating set problem in graph theory and the relevant minimum connected dominating set problem well describe the clustering approach to topology control [6]. Each node is either in a dominating set, or adjacent to a node in a dominating set. However, the problem of computing a minimum dominating set is known to be NP-hard [2], even when the complete network topology is known. Therefore, suboptimal solutions using a minimal dominating set (MDS), which is a subgraph of minimum dominating set and based on local minimum election of the dominators, should be used to approximate the calculation of the minimum dominating set. This work proposes a novel heuristic clustering approach to the election of cluster heads, which is equivalent to the computation of an MDS. The idea behind the approach is to make cluster heads form a quite stable backbone in highly dynamic vehicular environment. Therefore, partitioned connectivity caused by fragmentation is compensated to a certain degree.

### C. Cluster Head Election Algorithm

We have three observations while designing the approach of cluster head election. First, most message packets forwarded in VANET travel locally, same as what occurs in regular ad hoc networks [8], [12]. A vehicle moving in a highway, for example, has little interest on distributing traffic pileup warnings to vehicles 100 miles away. Second, according to the definition of MDS, the cluster head election information for any node should include only nodes that are one hop or two hops away from the node itself, since every node is one hop away from a cluster head. Third, too many cluster heads around the same set of nodes lead to no MDS [1], [10], [11].

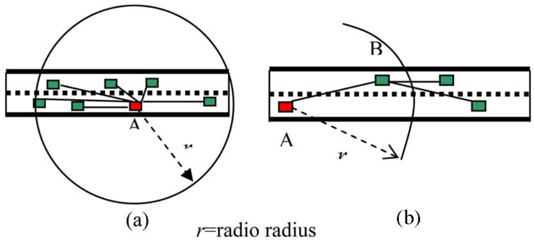


Fig. 2. Two conditions that make node A a cluster head.

Based on the earlier observations, every vehicle exchanges and maintains its neighbors' a priority value for each node information. The information is used for every node to calculate its priority in order to elect a cluster head among its two-hop neighborhood, such that any two nodes cannot have the same priority at the same instant during this stage. A node becomes a cluster head only if it satisfies the following two conditions.

1) The node has the highest priority in its one-hop neighborhood.
2) The node has the highest priority in the one-hop neighborhood of one of its one-hop neighbors.

Fig. 2 illustrates the two conditions that make node A the cluster head. Node A has the highest priority among its one-hop neighbors in Fig. 2(a). It has the highest priority among node B's one-hop neighbors in Fig. 2(b). The algorithm produces priorities distributing, which is normalized to [0,1).

While designing the criteria of computing priorities, we make two reasonable assumptions. First, every vehicle has limited travel time and distance on highway. Second, two neighboring vehicles do not have the exact same instant speed along their journey. Note that they can certainly have the same average speed over an entire journey. In other words, the relative speed is not zero all the time. To take into account the mobility associated with transportation information and the timestamp during the election of membership of MDS, we define the following criteria.

1) To increase the stability of cluster heads in MDS, vehicles having a longer trip are more qualified for being elected as cluster heads. A vehicle, which would travel longer time, is assigned higher priority; hence, at the very beginning of starting its travel, the expected travel time of a vehicle is calculated and announced using its desired driving speed and the geographic information system once its driver sets the destination.
2) To avoid elected cluster heads losing connectivity with their neighbors very soon, the eligibility of a vehicle should decrease quickly when its velocity has big difference from the average speed. Thus, a vehicle with large speed deviation is assigned lower priority.
3) Once a cluster head is elected and a cluster is formed, recalculating priorities is necessary only if the cluster is dismissed, and therefore, each node should compute its new priorities following the previous rules.

Many possible solutions can be used to compute the priority of a node while considering the aforementioned criteria. We define

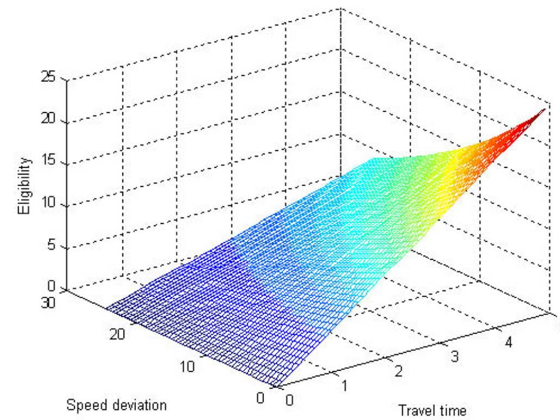


Fig. 3. Illustration of the eligibility function.

that the priority of node $i$ is given by the following formula:

$$p_i = \text{Hash}(t \oplus i) \oplus E_i. \tag{1}$$

A hash function is used to generate a unique priority for node $i$ according to the input of node ID, current time, and the eligibility function. The eligibility function $E_i$ is defined by

$$E_i = Te^{-0.2d} \tag{2}$$

where $T \in (0, T_{\max})$ is the estimated travel time and $d \in [0, 50]$ is the speed deviation. $T_{\max}$ is the maximal travel time. The units of $T$ and $d$ are minute and miles/hour, respectively. Fig. 3 illustrates the impact of the rules on the eligibility of a node. If a vehicle has long travel time and small speed deviation, its eligibility is high accordingly. To avoid the same eligibility value, each node must use a hash function to generate a unique normalized priority, as stated in (1).

## D. Cluster Registration and Updates

When node $i$ is powered up, it sets its cluster information to be ($i$, 0, 0, $g$, $p_i$) indicating that it is at its registration phase. It, then, searches for its neighboring nodes. If there is, at least, one node, it sends its cluster information to all of them. Upon receiving the cluster information of node $i$, each neighboring node adds $i$ as one of its neighbors. Each neighboring node that detects the existence of $i$ also sends its cluster information to node $i$.

When $i$ receives the cluster information from all of its neighboring nodes, it checks whether there is any registered neighboring nodes that are not in the registration phase. If yes, it tries to find a cluster such that the distance between the cluster head and itself is minimum and is less than or equal to the cluster radius $L$. If such a cluster is found, it joins the cluster and updates its cluster information. It, then, sends its clustering information to all of its neighboring nodes. Upon receiving the cluster information of $i$, each neighboring node updates its maintained information.

If $i$ finds that: 1) it has no neighboring node; 2) none of its neighboring nodes belongs to a specific cluster; or 3) it cannot find a cluster head that is within the cluster radius $L$, it forms a new cluster with itself as the cluster head and sets its

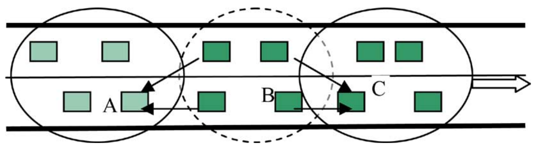


Fig. 4. Illustration of reconfiguration.

cluster information to be $(i, i, 0, g, p_i)$. Node $i$, then, sends its clustering information to all of its neighboring nodes, if any.

When $i$ detects the existence of a new neighbor, node $j$, and finds that $j$ is at its registration phase, $i$ replays its cluster information to $j$. Meanwhile, $i$ adds $j$ as a new neighbor and updates its information if $j$ decides to join this cluster. If $j$ is not at its registration phase and both $i$ and $j$ belong to the same cluster, node $i$ updates its cluster information and sends its new cluster information to all of its neighboring nodes. Otherwise, nothing else needs to be done.

When node $i$ receives the new cluster information from an existing neighbor node $j$, it updates the cluster information of $j$ in its routing table. If $j$ is the next node on the path from node $i$ to the cluster head, $i$ checks whether the new cluster information of $j$ is the same as the original one.

### E. Cluster Reconfiguration

If the distance between two cluster head nodes is detected less than the dismiss threshold $D$, the cluster with fewer members is dismissed to reduce communication overheads while its members join other clusters. Each node of this cluster launches a new registration stage to join other clusters. The threshold determines the rate of cluster reconfiguration, and also, depends on the radio transmission range. It makes no sense when the distance between two cluster heads is less than the cluster diameter $2L$. An example of reconfiguration is illustrated in Fig. 4.

## III. Performance Analysis of Stability

### A. Model

Assume that the spatial position of vehicles in a highway is confined to 1-D (line). But, in general, a two-lane highway network has different performance from that of a one-way four-lane highway network because of the influence of traffic capacity. Therefore, we model a cluster with a rectangle whose length is $2L$, twice the cluster radius. First, we define the following terms:

$v$: average velocity of vehicles;
$\rho$: average vehicle density;
$n$: number of lanes;
$w$: width of roadway;
$r$: efficient radio range;
$\Delta t$: time headway (time between two following vehicles passing a reference point);
$K$: average number of nodes in a cluster;
$d_e$: effective distance between two vehicles.

Traffic patterns depend on the traffic density, i.e., the number of vehicles per kilometer. At high densities, the complex interactions between neighboring vehicles make the modeling of such a dynamical system a challenge. Several vehicle spacing models are depicted in [19]. Here, an exponential distribution model is used with mean $N$.

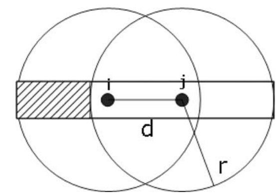


Fig. 5. Effective area when node $i$ becomes the cluster head.

### B. Cluster Stability

Although this proposal uses a node-prioritized MDS election algorithm based on the transportation parameters, the performance of the algorithm can be evaluated regardless of node priorities. Therefore, we consider the case in which each node has equal priority to analyze the probability of a node being elected as a cluster head. The probability of a node winning over $k$ other contenders is $1/(k+1)$. According to the previous model, the probability of a node winning among all contenders is

$$\sum_{k=1}^{\infty} \frac{1}{k+1} \frac{N^k}{k!} e^{-N} = \frac{e^N - 1 - N}{Ne^N}. \tag{3}$$

The probability that a node has, at least, one contender is simply $1 - e^{-N}$. If $N_1$ is the average number of one-hop neighbors of a node, for the first condition defined before, we have

$$p_1 = \sum_{k=0}^{\infty} \frac{N_1^k}{k!} e^{-N_1} \frac{1}{k+1}. \tag{4}$$

There are too many situations that lead to the second condition. Hence, we only consider the lower bound of the probability, that node $i$ becomes a cluster head when considering its one-hop neighbor $j$'s all neighboring nodes. Fig. 5 shows the relationship between nodes $i$ and $j$.

Since the roadway width is far less than the transmission range, only the nodes in the shaded area is effective for calculating the priority. So, the shaded area is approximately $wr$. According to the second condition, node $i$ should have a lower priority than the nodes in the shaded area, and, at the same time, have highest priority in node $j$'s one-hop neighbors. Therefore, the probability of node $i$ having a lower priority than the nodes in the shaded area is

$$p_2 = \sum_{k=1}^{\infty} \frac{(wr)^k}{k!} e^{-wr} \frac{k}{k+1}. \tag{5}$$

The probability that node $i$ has the highest priority among node $j$'s one-hop neighborhood is

$$p_3 = \sum_{k=0}^{\infty} \frac{N_1^k}{k!} e^{-N_1} \frac{1}{k+2}. \tag{6}$$

Since earlier events must happen simultaneously, the probability that node $i$ meets the second condition is $p_2 p_3$. Apparently, the two conditions defined are mutually exclusive; hence, the probability of node $i$ becoming a cluster head is

$$P_{\text{ch}} = p_1 + (1 - p_1)p_2p_3. \tag{7}$$

### C. Cluster Radius

Because

$$d_e = \frac{v\Delta t}{n} \tag{8}$$

and

$$K = \frac{2Ln}{d_e} \tag{9}$$

hence

$$K = \frac{2Ln^2}{v\Delta t} \tag{10}$$

$$L = \frac{Kv\Delta t}{2n^2}. \tag{11}$$

Because $\Delta t$ is a random variable, so is $K$. In [15], the distribution of time headway on highways is given. The typical mean time headway is 2–4 s. From (4), we learn that the cluster radius is determined by the average velocity of vehicles, the number of nodes in a cluster, and the number of lanes. If the average velocity increases, the space between two vehicles must also increase to ensure driving safety. Then, a larger cluster radius is needed. On the other hand, when the number of lanes is doubled, the cluster radius needs to be reduced four times. It is also easy to understand the relationship intuitively. More lanes lead to larger traffic capacity, and more members of a cluster if the vehicle density is fixed. To guarantee certain level of available radio bandwidth, the cluster radius has to be reduced so that effective spatial and frequency reuse can be achieved.

### D. Dismiss Threshold

In this proposal, a cluster is dismissed only when its cluster head is dismissed, and therefore, other nodes are reconfigured. When the distance between two cluster head nodes is less than or equal to the dismiss threshold $D$, clusters are reconfigured. Hence, we have the probability of cluster reconfiguration

$$P(d < D) = \int_0^D \lambda e^{-\lambda x} dx = 1 - e^{-\lambda D}. \tag{12}$$

The mean value of the given exponential distribution is $1/\lambda$. Therefore, from the definition of the effective distance, we have

$$\lambda = \frac{n}{v\Delta t}. \tag{13}$$

From (12) and (13), we get

$$P(\text{cluster\_reformation}) = 1 - e^{-nD/v\Delta t}. \tag{14}$$

At last, we have

$$P(\text{cluster\_reformation}) = 1 - e^{-KD/2Ln}. \tag{15}$$

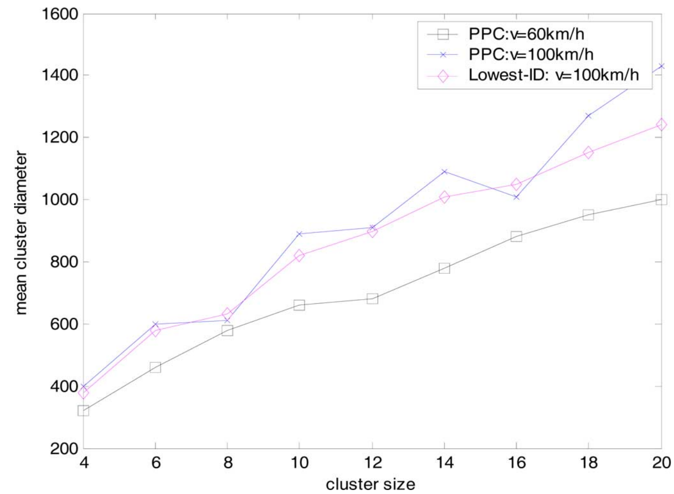


Fig. 6. Mean cluster diameter (two lanes) where PPC stands for position-based prioritized clustering.

According to (15), one can expect that a larger dismiss threshold leads to a higher rate of cluster head changes and higher probability of cluster reconfiguration. On the contrary, if $L$ increases, the probability decreases. Since the dismiss threshold is related to the transmission range, then, the probability of cluster changes is also related to the transmission range. Larger transmission provides longer distance for cluster heads to detect each other, and therefore, more frequent cluster reconfigurations occur. The next section shows the simulation results to demonstrate this conclusion.

## IV. Simulation Results

Extensive simulations are performed to study the characteristics of the proposed clustering technique using the microscopic vehicle traffic simulator, CORSIM, and the computer network simulator, NS-2. Developed by the Federal Highway Authority, CORSIM is able to provide vehicle traffic simulation data that are very close to real traffic data. The network used in the simulations consists of 100 vehicles moving in a highway with 10 km length. The packet length including the position information is 75 bytes. The traffic density is 50 vehicles/km per lane. The time headway is 2 s and the effective radio transmission range is 250 m. A comparative study of other clustering techniques is also conducted to evaluate the proposed method. Lowest ID and highest degree clustering methods are examined using the same configurations.

We first compare the mean cluster radius with different average cluster size when the average velocity changes. Fig. 6 shows that different average velocities affect the cluster diameter as discussed previously.

Then, simulations, as shown in Fig. 7, indicate that the number of lanes has significant influence on the cluster diameter due to higher traffic capacity.

One can also conclude that the mean cluster diameter is not strictly linear with cluster size, as (11) indicates. The main reason is that the movements of vehicles are not independent in the simulation experiments.

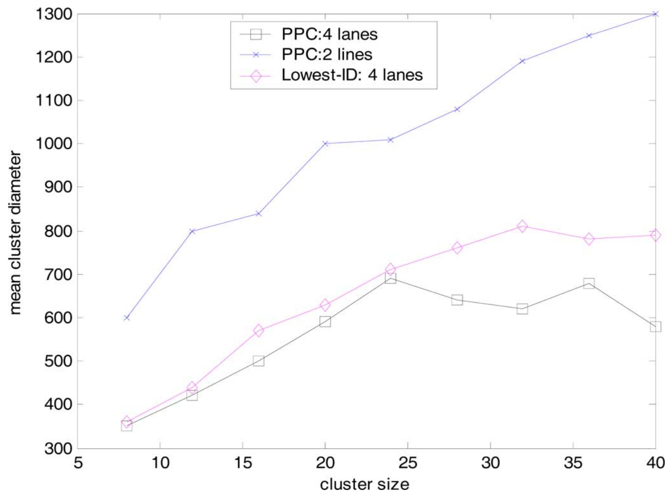


Fig. 7. Mean cluster diameter (70 km/h).

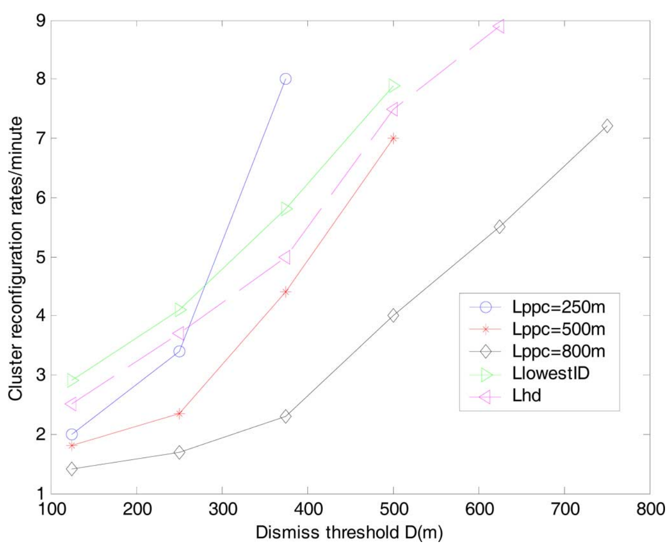


Fig. 8. Cluster reconfiguration rate versus dismiss threshold.

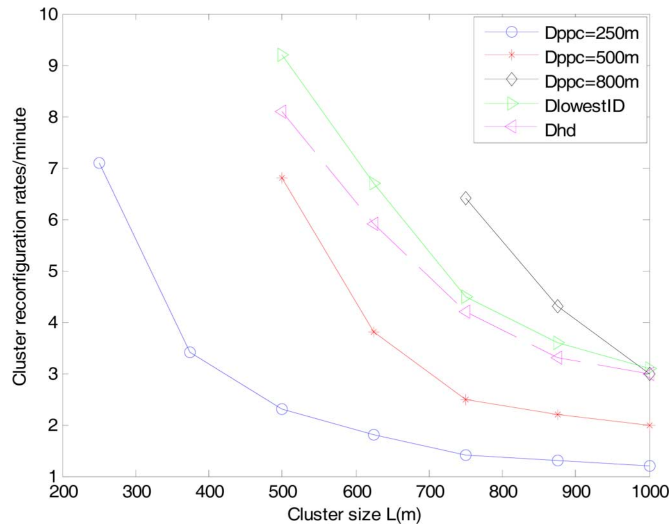


Fig. 9. Cluster reconfiguration rate versus cluster size.

A good clustering algorithm should be stable to radio motion, i.e, it should not change the cluster configuration too drastically when a few nodes are moving and the topology changes rapidly. The dismiss threshold $D$ determines whether a cluster should be dismissed or not, and it is critical for cluster reconfigured rate. It is desirable that a clustering technique incurs low cluster reconfiguration rate. Figs. 8 and 9 show the cluster reconfiguration rates of the proposed technique for various values of cluster radius $L$ and cluster dismiss threshold $D$. The performance of the regular lowest ID and the highest degree techniques is also presented in Figs. 8 and 9, and their $L$ and $D$ are both fixed at 500 m.

From the previous figures, the following observations are made: for a fixed value of the cluster radius $L$, the cluster reconfiguration rate increases as the cluster dismiss threshold $D$ increases. There are two reasons for this phenomenon. First, increasing the cluster dismiss distance increases the probability that the distance between two cluster heads becomes less than or equal to the cluster dismiss threshold. As a result, the probability of a cluster being dismissed also increases. Second, increasing the cluster dismiss thresholds decreases the probability that a member of the dismissed cluster successfully finds a neighboring cluster to join.

For a fixed value of the cluster dismiss threshold $D$, the cluster reconfigured rate decreases as the cluster radius $L$ increases. There are two reasons for this. First, when the cluster radius is larger, the members of the dismissed clusters have higher probability of finding neighboring clusters to join, resulting in the lower probability of forming one or more new clusters. Second, when a node moves away from its cluster head such that the distance from its cluster head is greater than $L$, larger cluster radius results in higher probability for the node to find a cluster head within $L$; therefore, the probability of forming a new cluster is lower.

The average aggregated link throughput versus transmission range is shown in Fig. 10. As a comparison, the lowest ID and highest degree clustering methods are also simulated to find the relationship between radio transmission range and the average aggregated link throughput. The results show that the proposed method significantly outperforms the traditional ad hoc clustering techniques in terms of throughput. The proposed method is more dedicated to fast-topology-changing ad hoc networks with high mobility.

The results confirm that there exists a tradeoff between transmission range and throughput. For a relatively smaller transmission range, the graph consists of several isolated subgraphs, with good spatial reuse but poor connectivity. Too small transmission range, however, leads to throughput decrease, since most of the clusters contain only one node and no links. As the transmission range grows, the proposal has better connectivity but less efficient spatial reuse, and thus, lower throughput.

Based on the earlier simulations, it is clearly shown that larger cluster size and smaller dismiss threshold lead to low cluster reconfiguration rate, which is equivalent to higher network stability. The radio transmission range of most wireless ad hoc

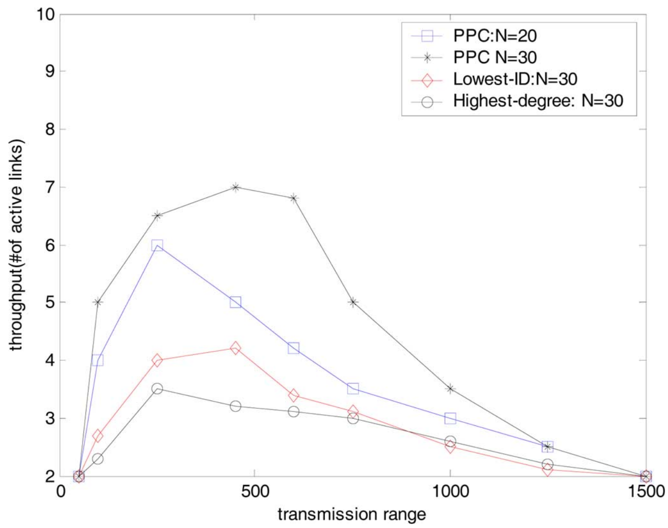


Fig. 10. Link throughput comparisons.

devices varies from 125–1000 m [6], [10], [12], [22]. However, from Fig. 10, we observe that the highest throughput can be achieved if the radius is from 250–700 m. Therefore, the ideal cluster size is about 800–1000 m, and the dismiss threshold is about 200–300 m, while a highway has a two-lane spatial capacity and moderate average velocity.

## V. Summary

In this paper, a new clustering technique for ad hoc vehicle networks is proposed. To achieve the stable cluster structure, a cluster is controlled by the priorities associated with vehicles' traffic information together with their geographical position information. Unlike regular MANETs, the performance of VANETs highly depends on vehicle traffic status. The predefined maximum distance between the cluster head and its members, then, controls the cluster size. It enables nodes to move during cluster setup and maintenance. The dismiss threshold controls the cluster reconfiguration. VANET can be considered as a 1-D network by taking the number of lanes into account. This paper performs basic mathematical analysis of PPC's performance under some assumptions. Simulations show that this new technique has nice flexibility and stability. Future research should include the influence in terms of available bandwidth and capacity. Studies of extreme cases such as sparse and jammed traffic should also be included in the future work. Security and other performance issues should be considered as well [24]–[28].

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