Cluster-Based Framework in Vehicular Ad-Hoc Networks

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Abstract. The application of Mobile Ad Hoc Network (MANET) technologies in the service of Intelligent Transportation Systems (ITS) has brought new challenges in maintaining communication clusters of network members for long time durations. Stable clustering methods reduce the overhead of communication relay in MANETs and provide for a more efficient hierarchical network topology. During creation of VANET clusters, each vehicle chooses a head vehicle to follow. The average number of cluster head changes per vehicle measures cluster stability in these simulations during the simulation. In this paper we analyze the effect of weighting two well-known clustering methods with the vehicle-specific position and velocity clustering logic to improve cluster stability over the simulation time.

1 Introduction

Vehicular Ad Hoc Networks (VANETs), an outgrowth of traditional Mobile Ad Hoc Networks (MANETs), provides the basic network communication framework for application to an Intelligent Transportation System (ITS). The U.S. Federal Communications Commission (FCC) has recently allocated the 5.85-5.925 GHz portion of the spectrum to inter-vehicle communication (IVC) and vehicle-to-roadside communication (VRC) under the umbrella of dedicated short-range communications (DSRC). This has fuelled significant interest in applications of DSRC to driver-vehicle safety applications, infotainment, and mobile Internet services for passengers.

Vehicles provide a robust infrastructure for the creation of highly mobile networks. In addition to providing a stable environment for the low cost and robust wireless communication devices typical of ad hoc networks, vehicles can easily be equipped with the storage, processing, and sensing devices necessary in any ITS implementation. A huge opportunity exists to leverage VANETs to enable a wide variety of service and societal applications.

VANETs have significant advantages over the traditional MANETs. Vehicles can easily provide the power required for wireless communication devices and will not be seriously affected by the addition of extra weight for antennas and additional hardware. Furthermore, it can be generally expected that vehicles will have an accurate

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knowledge of their own geographical position, e.g. by means of Global Positioning Satellite (GPS). Thus, many of the issues making deployment and long term use of ad hoc networks problematic in other scenarios are not relevant in MANETs.

In addition, there is a wealth of desirable applications for ad-hoc communication between vehicles ranging from emergency warnings and distribution of traffic and road conditions to chatting and distributed games. As a consequence many vehicle manufacturers and their suppliers are actively supporting research on how to integrate mobile ad hoc networks into their products.

Vehicles in a VANET environment move within the constraints of traffic flow while communicating with each other via wireless links. Ah hoc networks use less specialized hardware for infrastructure support and leave the burden of network stability on the individual nodes within the network. Without routers, or other dedicated communication hardware, a possible method to optimize communication within the network is to develop a hierarchical clustering system within the network. This clustering system would identify certain lead or cluster head vehicles that act as the relay point of communication between vehicles local to that node and other vehicle clusters. To support the dynamic nature of the VANET environment, the vehicles clustering must be periodically updated to reflect topological changes and vehicle movements. Clustering within the network must be very fast to minimize time lost to clustering [16].

Association with and dissociation from clusters, as a result of the mobile nature of VANET nodes (vehicles) perturb the network and cluster selections. Cluster reconfiguration and cluster head changes are unavoidable. Therefore, a good VANET clustering algorithm should seek to regulate rather than eliminate cluster changes. This algorithm should also maintain cluster stability as much as possible during vehicle velocity and acceleration changes and/or traffic topology shifts. Otherwise, the overhead of cluster re-computation and the involved information exchange will result in high computational cost and negate the benefits of VANET communication. The ideal VANET cluster will maintain its cluster head and members over the longest possible time range. This concept will be explained and evaluated further later in this paper.

A significant amount of research focuses on optimal methods for clustering nodes in MANETs. VANETs, however, pose new challenges in cluster head selection and network stability. VANETs must follow a tighter set of constraints than MANETs, and therefore require specialized clustering algorithms. First, nodes or vehicles cannot randomly move within the physical space, but must instead follow constraints set in place by the real road network topology. Second, vehicle movements follow well-understood traffic movement patterns. Each vehicle is constrained by the movements of surrounding vehicles. Third, vehicles generally travel in a single direction and are constrained to travel within a two-dimensional movement. Given these movement restrictions and the knowledge of position, velocity, and acceleration common available to on-board vehicle systems it is possible to approach clustering more intelligently and possibly discover a better clustering methodology for VANET environments.

The constrained environmental conditions of VANETs warrant a constrained simulation environment. Many simulation tools and environments have been designed for MANET implementations. These tools, however, fail to adequately model the needs of a VANET network. Compared to the random movements modeled in MANET environments, VANET simulation movements must behave according to traffic patterns in terms of car-following, lane-changing, directional movement, velocity, and acceleration among others. Current MANET simulation environments cannot be considered suitable for VANET simulations even in the broadest sense. Therefore, simulation of the network environment is best performed with traffic micro-simulation tools. For the purpose of this study, simulation and traffic modeling was performed using a micro-simulation tool specially modified to perform randomized vehicle-based clustering under a number of algorithms and traffic constraints. This approach also allows further research on traffic statistics and flow improvements as a result of network communication. Further modifications to the environment were made to log vehicle cluster, position, velocity, and acceleration states during simulation activity.

This research concerns the augmentation of two well-known clustering algorithms with two additional traffic-specific algorithms to determine whether the clustering stability can be improved for VANETs. This works focuses on simulation of these algorithms in a constrained micro-simulation environment using a compound-weighting scheme devised at part of this work. Additionally, this document discusses a utility function implementation for determining the vehicle cluster head selection priority based on a multiple-metric weighting algorithm.

2 Backgrounds and Related Work

2.1 Clustering in MANETs

Communication network clustering organizes the network nodes into a hierarchical arrangement. Figure 1 provides and example of the organization of twelve nodes into three clusters. The basic communication capability between the twelve nodes is outlined as connections between the bottom tier of the hierarchy. These twelve basic nodes are then grouped into clusters using some algorithm. In the upper tier of Figure 1, the three cluster head nodes are displayed with connections between them representing the possible message paths under the cluster-constrained network [8,9, 14].

This clustered architecture reduces the communication relay points for each node to a small subset of the total network. Each cluster head aggregates local member topology and acts as a relay point for communication between its members and members of other clusters. This reduces the messages exchanged between individual network nodes and the overhead of information stored within those nodes [13].

Attention on clustering in MANETs has increased considerably as wireless technologies improve and MANET theories become practice [1,2,3]. Most of these approaches embrace the role of a cluster head that maintains the cluster and provides the entry point of that cluster into the broader network. Among several proposed cluster head selection algorithms the predominant approaches are the (i) Lowest-ID algorithm and (ii) Highest-Degree algorithm. Recent work has simulated the performance of these algorithms using random placement in a square grid with multi-directional node movement [2,4,7]. As previously stated, this does not translate well into the VANET environment.

This research does not consider network broadcasts requiring more than one hop in communication. This simplifies the overall communication and clustering strategy and reduces the overall bookkeeping necessary to maintain the clusters. This approach seeks to obtain optimal results by adding traffic-specific information to the clustering logic.

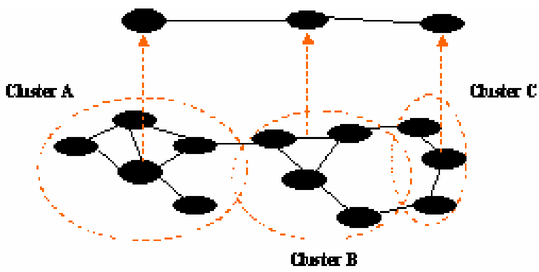

Fig. 1. Clustering within a 12-node MANET environment

2.2 Lowest-ID Algorithm

The Lowest-ID algorithm involves the selection of cluster heads by means of an absolute ordering of a fixed vehicle ID attribute. Cluster formation is performed using node-level election of cluster heads. During the clustering stage, each node within the network broadcasts its ID to all other reachable nodes. Each node, in turn, chooses as its cluster head the node with the lowest ID. This method has been discussed in great detail [4,5,6] in a number of works and is well known for its stability in general MANET applications. In each cluster, the node within range with the lowest ID becomes a cluster head and maintains the cluster membership information of all other nodes.

This simulation study in this research randomly assigns the ID values to each vehicle in the simulation. This approach approximates real-world situations in which the ID attribute relates to the MAC ID of the network hardware. The ID attribute of a vehicle is fixed for the lifetime of that vehicle. This property explains why repeated cluster head selection from a local set of vehicles tends to reselect previous cluster heads.

2.3 Highest-Degree Algorithm

This algorithm uses the degree of the nodes within the network to determine the cluster heads. The general idea that choosing high-degree nodes as cluster head candidates tends to uncover larger clusters. In MANET implementations, however, small movements in network nodes can often lead to a large number of degree changes throughout the network. This, understandably, has a detrimental effect on the stability of the clusters over time [4,8]. So cluster heads in Highest-Degree implementations are not likely to maintain cluster head status for long.

Table 1. Summary of the two algorithms

Algorithm	Strengths	Weaknesses
Lowest-ID	Fast and simple, Relatively stable clusters.	Small clusters, long cluster head duration.
Highest-Degree	Most connected nodes appropriately given higher priority.	Relatively unstable clusters.

Many additional clustering algorithms have been defined to meet special-case purposes. These algorithms are included in this research because they have constant time complexity and good scalability. For convenience, these algorithms have been summarized in Table 1.

The Lowest-ID clustering was generalized to a weight-based clustering technique, referred to as the DCA (Distributed Clustering Algorithm) in [2,8,15]. Our implementation will not consider network broadcasts requiring more than one hop in communication. This simplifies the overall communication and clustering strategy and reduces the overall bookkeeping necessary to maintain the clusters. This approach seeks to obtain optimal results under realistic traffic flow simulation.

3 Transportation-Specific Clustering Methodology

Review of current MANET research highlights the need for a transportation-specific review of clustering methodology and the discovery of traffic-optimized clustering schemes. This research chose to design a utility-based methodology for network cluster formation. In this approach, each vehicle implements some form of utility analysis of each proximally located possible cluster head. Periodically, each vehicle will broadcast general network information such as ID and current degree as well as vehicle-specific traffic statistics such as position and velocity. Upon receipt of this information, each vehicle chooses a cluster head by evaluating the utility of each potential head. The node with the highest utility is selected as the cluster head.

3.1 Utility Function

A utility-based approach to clustering requires the creation of a vehicle-specific agent model for periodic cluster formation. This model was implemented by augmenting each vehicle in a traffic micro-simulation platform to periodically determine and store cluster head information. The cluster head determination algorithm was implemented in a single weight method that produced a weight value for each vehicle with which the current vehicle can communicate. After implementation of this method, the Lowest-ID and Highest-Degree methods were implemented and tested [17]. This research applies compound clustering schemes based on the compound weighting of the Lowest-ID and Highest-Degree algorithms and the traffic specific Position and Closest Velocity to Average algorithms to find a more stable clustering method for use in VANET environments. The belief is that these traffic-specific algorithms will be better predictors of the common traffic situations that lead to cluster dissociation. Thus the new algorithms should augment the well-known and stable MANET clustering techniques to obtain a more stable technique for the constrained VANET problem.

As an important note on this investigation, an exhaustive investigation of vehicle parameters and parameter-specific cluster methods was not performed or intended. Many other vehicle state measurements exist and are equally predictors of traffic movement, but have been fixed for this experiment.

The two clustering methods used to attempt a stability improvement in the Highest-Degree and Lowest-ID algorithms are as follows:

a) Closest Position to Average: A vehicle attempts to choose as its cluster head in order of the absolute difference of candidate's position to the average position of all proximal vehicles.
b) Closest Velocity to Average: A vehicle attempts to choose as its cluster head in order of the absolute difference of candidate's velocity to the average velocity of all proximal vehicles.

These steps outline the procedure for implementation of this utility function:

1. Each vehicle determines the vehicles within range by polling the local broadcast region and tracking the candidate cluster head set C. All vehicles with broadcast range are considered candidate cluster heads.
2. Using candidate set C and the state information received by broadcast, each candidate is evaluated using the utility function.
3. The cluster head is chosen in decreasing order of utility. The petition for cluster membership is broadcast to the chosen vehicle. Should the chosen vehicle deny the request the vehicle with the next highest utility is selected and this step repeated.

A vehicle may deny the selection as cluster head if it has reached its maintainable limit of cluster members or if the vehicle has already chosen to join with another cluster head. Note, a vehicle may elect itself as its cluster head. Random selection of vehicles simulates asynchronous cluster formation at fixed time intervals.

3.2 Vehicular Considerations of Cluster Formation

Due to the dynamic nature of traffic flow, the member vehicles as well the cluster heads tend to move in semi-related motion throughout the roadway. This motion destabilizes the network clusters and warrants periodic cluster reformation. Reclustering may result in transition of nodes from one cluster to another, split of a cluster into more than one cluster, or convergence of multiple clusters into a single larger cluster. The frequency of cluster formation and cluster change is thus an important consideration in algorithm evaluation.

Equally important is the size of each cluster. Resource and relay algorithm performance considerations may limit the manageable size a cluster head's cluster. For simplicity this research used a common fixed upper bound on all vehicle's cluster size. The implication is that vehicles may reject nodes within range due to resource exhaustion.

The delicate balance between cluster size and coverage has major implications in network communication latency and throughput. Each vehicle communicates with vehicles in other clusters through the selected cluster heads. Care must be taken to ensure that the head selection algorithm does not have the unfortunate result of adding network transmission bottlenecks. Alternately, algorithms that yield too many cluster heads may result in a computationally expensive system. An important area of study is the selection of cluster algorithms that balance high throughput and lowest latency. The performance of the new algorithms must be measured relative to previously analyzed MANET algorithms. The objective of this research is to evaluate the number of cluster changes and the cluster size for simple combinations of the Highest-Degree and Lowest-ID algorithms with the Position and Closest Velocity to Average methods to determine whether traffic-specific augmentation can improve stability in VANET environments.

MANET research covers many compound or multi-dimensional clustering algorithms. In general, these methods are presented to overcome certain disadvantages of general MANET models such as power consumption, low mobility, or random multi-directional movement. These algorithms have not been modeled because their contributions to VANET implementations are not immediately apparent. Instead, general-purpose compound algorithms using traffic-specific information have been implemented to obtain a better overall clustering technique.

3.3 Weighted Clustering

This research utilized a weighting scheme incorporating traffic-related information and multiple clustering techniques. In this approach, the Lowest-ID and Highest-Degree clustering logic is augmented with traffic-specific logic. The goal of this research is to improve on the basic MANET clustering by applying domain-specific logic to aid in cluster head selection. This implementation uses a weighting scheme of 85% weighting to the Lowest-ID or Highest-Degree logic and 15% to the traffic-specific information of position or velocity. The desire is to improve upon the initial clustering logic to obtain better stability over the simulation time.

$$\text{Equation 1: Utility} = \text{Sum}\ (W_j * \text{Rank}_{j...})$$

The weighting algorithm calculates a weight for each potential cluster head using normalized results from each of the component algorithms. Equation 1 shows the method for aggregating weights of each of the cluster methods. Using the rank of each vehicle after clustering with the initial methods, the compound rank or utility is calculated using the method of Equation 1. After each vehicle's compound utility is determined, the vehicles are selected as cluster heads in order of highest utility.

4 Simulation Study

This study modified Traffic Simulation 3.0 [10], an Intelligent-Driver Model (IDM) [11] micro-simulation tool built to monitor traffic flow under various basic highway configurations. This environment simulates accelerations and braking decelerations of drivers (i.e. longitudinal dynamics), and uses the Minimized Overall Braking Induced by Lane changes (MOBIL) lane change model. All model parameters and the initial simulation source code are available at [10].

4.1 Implementation

The source code for the aforementioned simulation tool was modified to perform fixed interval cluster formation using six experimental algorithms (Lowest-ID, Highest-Degree, Lowest-ID augmented with Position, Lowest-ID augmented with Closest Velocity to Average, Highest-Degree augmented with Position, Highest-Degree augmented with Closest Velocity to Average) using a utility function based on our compound weighting scheme. To simplify this study, only simple two-dimensional compounding was analyzed.

To further constrain this simulation, the weights for each algorithm were fixed to use an 85% weight for the MANET algorithms and 15% weight for each of the two traffic algorithms studied.

4.2 Metrics

In addition to utility function and display changes, periodic state logging was implemented. This data provided the basis for the simulation result analysis and algorithm comparison. To measure the system performance, two metrics were identified: (i) the average cluster head change per step and (ii) the average cluster size. Metric (*ii*) alone does not accurately depict system performance, so the relative measurement (*ii*)/(*i*) was introduced to provide a reasonable comparison metric between the analyzed algorithms. A method is considered relatively better if it has either better stability using metric (*i*) or larger average cluster size.

5 Results Discussion

The simulation results represent the performance of each algorithm across various wireless transmission range values (0-300 meters) and maximum vehicle speed (40-140 kilometers/hour) with a fixed maximum cluster size of 50 vehicles. In addition, the simulation time duration was held constant across all tests. To minimize traffic flow variability between simulations and enable repeatable test results, the randomized features of the model were seeded with the same value at each simulation run.

Figure 2 summarizes the variation of the average number of cluster head changes with respect to the transmission range. It illustrates the performance of all six algorithms for a reasonably standard traffic flow environment with a fixed maximum speed of 100km/h. Notably, the algorithms based on the Lowest-ID clustering show rapid initial increase of cluster head changes as a result of transmission range increase. These algorithms quickly converge, however, in line with the uniform

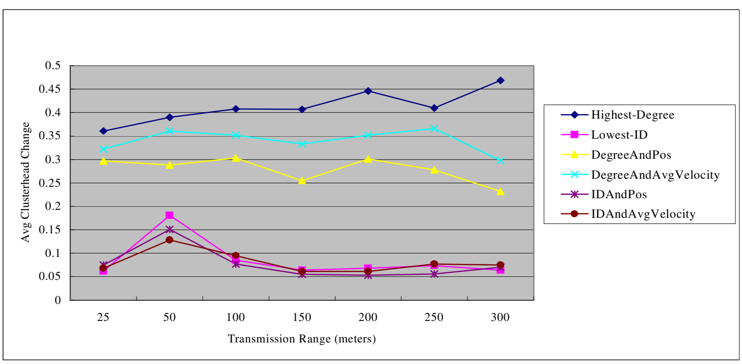

Fig. 2. Changes vs. Transmission Range

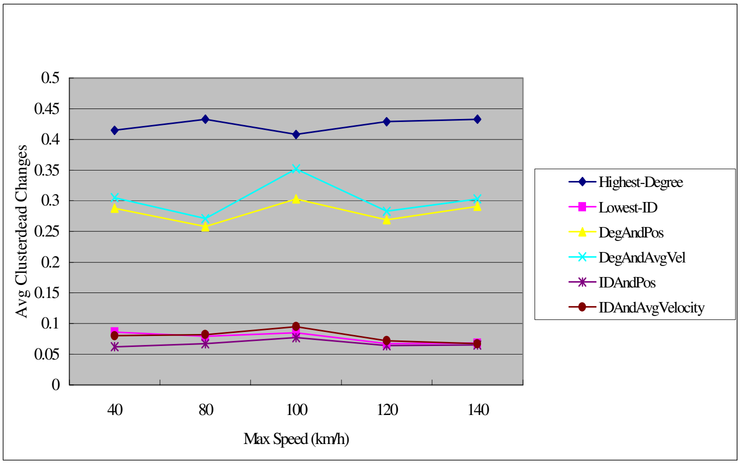

Fig. 3. Changes vs. Max Speed

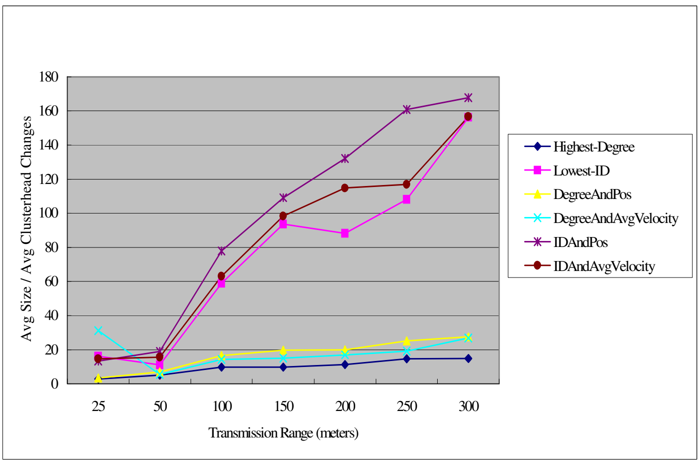

Fig. 4. Clustering Ratio vs. Transmission Range

distribution of the randomly generated ID values and vehicles in the Intelligent Driver Model [11]. For small transmission ranges, most vehicles remain out of each other's transmission range. This leads to a severely disconnected network. For the other algorithms, the likelihood of change in either of the metrics as a result of increased transmission range results in a steady increase in the number of clusters with transmission range. The three Lowest-ID algorithms clearly perform better than the three Highest-Degree algorithms. The simple Highest-Degree method proved to have the poorest performance. Clearly, the addition of traffic-specific information to the Highest-Degree clustering enabled more stable clusters. The three Lowest-ID algorithms show very similar performance. The traffic-specific logic did not have as great an effect on an already well-performing algorithm, but did help reduce the initial peak values seen with the simple method at a 50m range. Traffic patterns show that similarly located vehicles are more likely to share similar velocities. As a result, the algorithms weighted with Position and Closest Velocity to Average clustering logic tend to have a high correlation, but different overall performance.

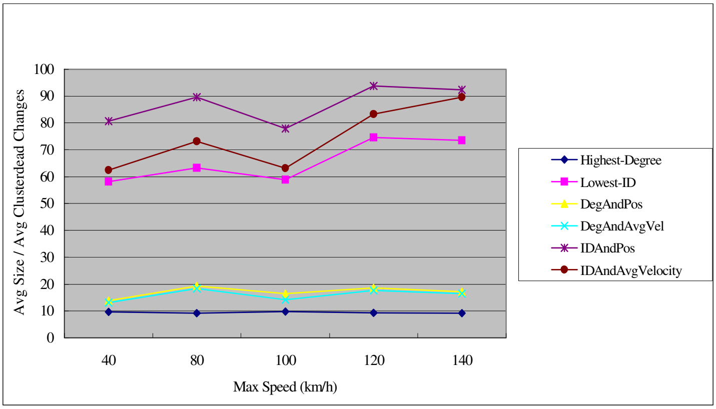

Fig. 5. Clustering Ratio vs. Max Speed

Figure 3 shows the effect of varying the maximum speed on the average number of cluster head changes with a fixed transmission range of 150m. Algorithm performance is consistent with those of Figure 2. Speed limits are only useful only in heavy-traffic situations. [10]

Figure 4 displays the performance of all algorithms over various transmission ranges. Higher curves indicate better overall performance. Figure 5 shows the overall performance across various speed limits.

6 Conclusion

The analysis performed in this research highlights the performance of the Lowest-ID clustering algorithms as optimal for the constrained MANET environment provides by VANETs. As in MANET studies, the Lowest-ID provides a stable cluster topology over long time durations due to its nature as an unbiased, uniformly distributed clustering methodology. The addition of traffic-specific clustering logic to this basic algorithm in a compound-weighted scheme did not provide any noticeable improvement. Some stability gain was realized, however, but the additional overhead may not justify the added complexity.

The study of the augmented Highest-Degree methods did, however, show some noticeable improvement when the traffic-specific logic was added. This result shows the potential for improvement of well-known and trusted MANET clustering algorithms when used in VANET environments and the advantage of applying domain knowledge to the specific MANET problem.

This study focused on a small subset of algorithms in an attempt to realize such a gain. Further research should be performed to realize further gains and determine optimum performance across the many possible compound-weighting scenarios.

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