A survey on the characterization of Vehicular Ad Hoc Networks and routing solutions

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ABSTRACT

During the last five years, the Federal Communication Commission allocated a frequency spectrum and established public and private service rules for inter-vehicles and vehicle-roadside communications. A moving vehicle can use the frequency and services to connect to other vehicles and form a Vehicular Ad Hoc Network (VANET). VANET is a wireless network composed of vehicles and roadside beacons without central access points. Although rich literature in ad hoc networks exists, the scale, availability of realistic traffic data and vehicle equipments motivate researchers to study the unique characteristics of VANET. Also, the characteristics of VANET pose new challenges for existing routing protocols. In this paper we survey and compare literature on the characterization of VANET. We then examine current routing solutions designed for the characteristics of vehicular networks. Finally, we share a collection of useful references and future research directions.

1. INTRODUCTION

In 1999, the Federal Communication Commission allocated a frequency spectrum for vehicle-vehicle and vehicle-roadside wireless communication. In 2003, the Commission then established the service and license rules for Dedicated Short Range Communications (DSRC) Service. DSRC is a communication service that uses the 5.850-5.925 GHz band (5.9 GHz band) for the use of public safety and private applications [1]. Vehicles and beacons on roadsides can form a Vehicular Ad Hoc Network (VANET) using the allocated frequency and service to communicate with each other without central access point. Many consider Vehicular ad hoc networks (VANET) as one of the most prominent technologies for improving the efficiency and safety of modern transportation systems [2].

Vehicular Ad Hoc Network shares some common characteristics with general Mobile Ad Hoc Network (MANET). Both VANET and MANET are characterized by the movement and self-organization of the nodes. They are also different in some ways. MANET can contain many nodes that cannot recharge their power and have un-controlled moving patterns [3]. Vehicles in VANET can recharge frequently, however can be constrained by the road and traffic pattern.

The characteristics of the network can affect the routing strategy. There are existing protocols designed for the characteristics of MANET, but further studies are required to evaluate the suitability of existing protocols for VANET. Existing routing protocols are generally categorized in *topological-based* and *position-based* routing. Topological-based routing makes use of global path information and link information to forward packets. Position-based routing does not keep global network information but requires information on physical locations of the node. In [4] a survey on topological routing are provided and the survey in [5] explores position-based routing in general.

Other than the unique characteristics and routing issues in VANET, the popularity of GPS system, availability of traffic data and a wide range of commercial and public applications motivate new characterization studies and routing proposals to fit the needs.

In this paper we survey existing works on the characterization of VANET and explore the effects of the characteristics on routing. Unlike existing detail survey for general MANET, we provide representative routing protocols that adapt or utilize the unique characteristics of VANET.

This rest of the paper is organized in four sections. In section two we explore the literature on the characterization of VANET and compare their results. Section three provides representative routing solutions based on three categories: location-based, enhanced topological-based and hybrid approach. We give the direction of future research in section four and a summary in section five.

2. CHARACTERIZATION OF VANET

We explore the unique characters and requirements of VANET in five major areas: (1) mobility and network characteristics, (2) available technologies, (3) operating environments, (4) application requirement, and (5) security.

2.1. Mobility and Network Characteristics

In the section, we explore the characteristics of mobility and network behaviors such as connectivity, connection lifetime, and multi-hop organization. Most current works uses simulation software to gain understanding in this area. These works establish mobility model to simulate node movement in the network and network model to represent the network layers. In the following, we look at the models of representative works in detail and compare their results.

Mobility models for ad hoc networks are widely researched in the literature. Recently, a wave of new researches in VANET mobility appears because (1) many believe the speed, scale and dynamics of vehicular networks make VANET more unique and specialized than general mobile ad hoc network and (2) the availability of actual traffic and map data provides opportunities to study realistic vehicular movement. In this section, we study the recent researches that focus on the mobility and network characterizations of a vehicular ad hoc network.

Figure 1 shows the categories we use to differentiate existing mobility and network models. Similar to [6], we categorize the existing mobility models according to the level of detail and degree of randomness. We consider three major level of detail: (1) Microscopic, (2) Mesoscopic, and (3) Macroscopic. Microscopic model describe the behavior of individual nodes and is the most detail. Mesoscopic level includes the homogenized movement of a group of vehicles. Macroscopic model describe entire system in a fluid flow model [7]. Like [8], we categorize the degree of randomness in three groups (1) trace based, (2) constrained topology, and (3) statistical. We also examine the network model based on the level of details. In the following sections, we categorize the recent works describing the characterization of vehicular ad hoc network and compare their findings.

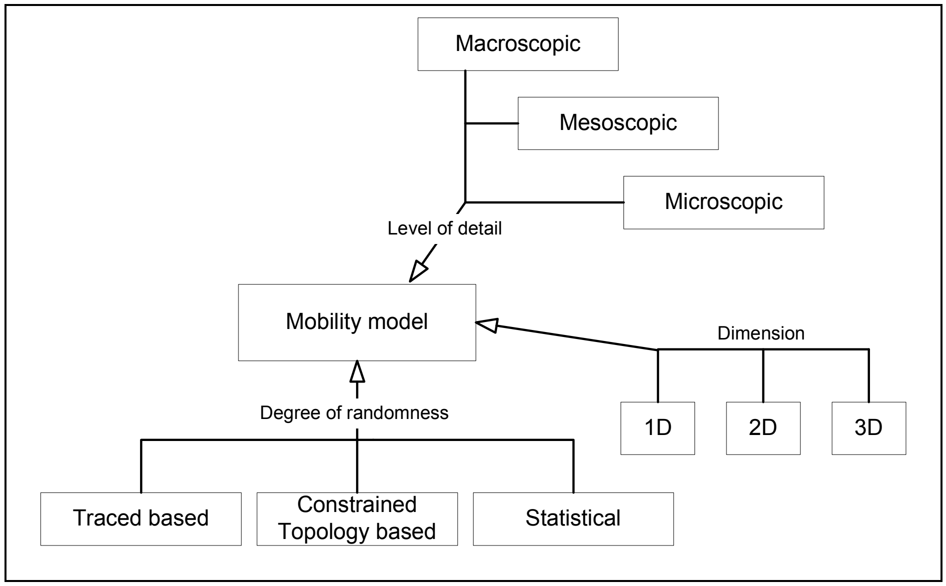

Figure 1: Mobility model categories.

Artimy et al study [9]: The authors develop a microscopic simulator to investigate the effects of free-flow traffic on connectivity in a vehicular ad hoc network. An imaginary road is divided into fixed length segments. Either none or exactly one car is traveling at a velocity in each segment. The movement of individual vehicle is controlled by a set of driving rules such as acceleration and deceleration based on the distance and velocity to neighboring vehicles. As a result, all vehicles appear to follow similar velocity and lane changing restrictions. At each simulated time step, the output of the traffic simulation model is used to construct a connectivity graph. The graph nodes represent the vehicles and the paths represent communication links between two nodes.

The study finds that vehicle density, relative velocity and number of lanes are the key factors that influence node connectivity. Vehicle density refers to the number of vehicles in the system. Relative velocity is defined as the differences in velocity between any two vehicles. The study indicates that the distance between two vehicles does not affect the connectivity directly because the transmission range can be adjusted allow for a distant node to sense each other. The effects of interferences and signal fading due to distance are not considered in the simulation.

Saha et al study [10]: The authors develop a mobility model based on actual map data and simulate the Dynamic Source Routing protocol on the model. The model converts portions of the publicly available TIGER database from the U.S. Census Bureau into a graph data structure. Mobile nodes are injected in the system to move along the paths in the graph. A vehicle starts on a random point in the graph and a destination is randomly chosen for the vehicle. The driving behavior of the driver is simulated by the assumption that a driver would always drive to a destination following the shortest path. The authors use the standard Dijkstra's single source shortest path algorithm to calculate the route from source to destination. Once a vehicle arrives at the destination, another destination is randomly chosen for this vehicle, thus it starts the process again.

The study results show that the constructed mobility model produces similar results as the statistical Random Waypoint model in many cases. The studies indicate that transmission range under 500 meters produce severe network fragmentation. Like [9], the study finds that vehicle density improves connectivity. DSR deliveries about 90% of packets with acceptable latency in networks of 150 nodes with wireless transmission range of 500 meter.

Wang's study [11]: This paper used a commercial microscopic traffic simulator (VISSIM). Their road setup is a closed three lanes highway (total length is 26 Km) without entry and exit. The authors claim the acceleration/deceleration, lane-changing, car-following, and other behaviors are simulated using models well developed in the literature on transportation. The metrics on connection lifetime are collected for vehicles communicating with vehicles moving in reverse direction only, same direction only, and both directions. Their result showed 91% of all unicast paths have a lifetime less than 50 seconds. The result also compares the unicast path lifetime and the initial path length in hops. They find that lower hop count will led to longer unicast path lifetime.

Blum et al study [12]: The authors claim that Inter-vehicle communication networks differ from typical MANET models in four areas: (1) rapid but more predictable topology change, (2) frequent network fragmentation, (3) small effective network diameter, and (4) path redundancy that is limited temporally and functionally. This work uses a commercial microscopic simulator, CORSIM, to simulate an inter-vehicle network and explores the implications of the results on the inter-vehicle communication network. The authors simulate road geometry to correspond to the 9.2 miles of highway with 10 exits and 10 on ramps. Unlike other simulation studies that often assume all vehicles are equipped with wireless equipment, this study assumes about 20% of the vehicles have the equipments. The network model is simulated using the NS simulator.

The results conclude that network layers need to effectively use the limited bandwidth, and efficiently function in the rapidly changing topology. The following is some key findings:

1. The connection lifetime is affected by the direction of the vehicles and the radio transmission range.
2. Even for vehicles traveling the same direction with long transmission range (about 500 ft), the links are still very short-lived (about 1 minute on average).
3. Sending even a relatively small message over 3 or 4 hops is likely to suffer a route error. At about 9 hops, the path disappeared before the fist packet can be acknowledged.
4. The limited route lifetime becomes even more acute if multiple routes are needed simultaneously.
5. Increasing the radio range to increase link stability, path life or network connectivity, will increase the interference on the transmission and hence decrease the network throughput.

Chen et al study [13]: This paper studies how traffic density can affect the delays of the VANET. It uses a microscopic traffic simulator called CORSIM (CORridor SIMulator), which is developed by the Federal Highway Administration. Their network simulator accounted for the traffic exiting and entering the traffic simulator model. The result shows that the lower density it is, the higher delay for the message delivery. This paper also compares the delay results on different routing algorithms (optimistic vs. pessimistic), different highway directions (unidirectional vs. bi-directional), and different number of lanes (1-5 lanes). In pessimistic forwarding, message is dropped when no next hop exists. In optimistic forwarding, messages without next hops are kept by the intermediate nodes. Following is some key findings:

1. Delays in pessimistic delay rises more sharply than in optimistic delay indicating that the messages remain on the intermediate nodes have a chance to be forwarded to new nodes entering the transmission range, thus decreasing the latency.
2. According to a result, applications can increase their tolerance of delay (e.g. 200 seconds) and use optimistic forwarding to work in a less dense network.
3. When optimistic forwarding is used, the delay at any given density is lower for bi-directional traffic, indicating that the rapid relative motion of vehicles in two directions maximizes the benefits of optimistic forwarding.
4. With 3 or more lanes, the observed delay is lower than with 2 or less lanes. This indicates three or more lanes provide enough freedom of movement to prevent vehicle to cluster together due to a few slow moving vehicles.

Jetcheva et al study [14]: This study obtains the mobility data from several weeks long traces for the movement of city buses in Seattle, Washington. The city bus system is composed of over 1200 vehicles covering a 5100 square kilometer area. The city owns a location system that tracks each bus using a combination of odometer and signpost transmitters. The city puts the location data online for Internet users to monitor the location of each bus in real-time. The authors record the online data and convert the recorded data into movement patterns suitable for use in NS-2 network simulator. The buses are assigned to different transmission power, from 1 km to 3 km, based on the distance they travel. The speed reported by the bus shows 90% of the average speeds being less than 10 miles per hour and 97% being less than 20 miles per hour. Their results indicate that the lowest transmission range studied (1 km) cause substantial network partitions. At a range of 1 km, the median node degree, which indicates the number of other nodes that this node is connected to, is 30.

Also, they find that without any base stations, with transmission range of 1.5 km, the maximum path length is up to 48 wireless hops. They added 8 base stations in the various areas and find that the maximum path length decreases to 20 wireless hops. The findings regarding number of hops have great implication on whether it is realistic to expect two far apart nodes can communicate without access points. As we see in [12], the first packet will not be acknowledged before the link expires even with only 9 hops. Based on the results, we expect that communications between far apart nodes will require other access point connections.

2.1.1. Comparisons and Analysis

All six studies use a microscopic simulator to simulate the motion of each vehicle in a vehicular ad hoc network. Researchers in [14] have done some field experiments, but still rely on simulators to simulate network communications. All the works do not have a detail network model that accounts for network contention or transmission errors.

Literature	Mobility Model	Network Model/Transmission Range
Artimy et al [9]	-Microscopic simulator, 129 km/hour -Topology: multi-lane highway, unidirectional, closed	Connectivity graph with no delays or errors / 250 meters
Saha et al [10]	-Microscopic traced based, 35-75 miles/hour -Topology: Traces on a portion of actual map including highway and streets	NS-2 Simulator with DSR routing / 500 meters
Wang [11]	-Microscopic simulator, 80-110 km/hour -Topology: multi-lane highway, bi-directional, closed, constant vehicle density (2000 vehicles).	Connectivity graph with no protocol layers / 100 meters
Blum et al [12]	-Microscopic trace based -Topology: Traces on a portion of a highway, Bi-directional.	NS-2 simulator / 25 – 500 feet
Chen et al [13]	-Microscopic simulator, 50 MPH speed limit -Topology: a straight multi-lane highway, bi-directional.	Simulator with pessimistic and optimistic forwarding / 200 meters
Jetcheva et al [14]	-Microscopic trace based: 1200 vehicles covering 5100 square km area, 20 miles/hour on average -Topology: city map.	- NS-2 simulator / 1-3 km

Table 1: Mobility and network models used by the literature for understanding the network and movement characteristics of VANET.

Table 1 summarizes the traffic and network model of the studies presented. Both [9] and [11] simulate the road as a closed straight road with no exit or entrance. The result may not be realistic because vehicles exiting and entering the road may affect the number of the hop and lifetime of the path. On the other hand, studies in [10], [12], [13] base the topology on real maps. Jetcheva's study in [14] is the only one which document the detail traffic trace collection procedures, however, the average speed of most vehicles is less than 20 miles per hour and the transmission range is very large. The topology used in [10] contains a mixture of road types including highway and city road. While study in [13] focus on traffic on a highway, study in [14] collects traces in city road only. Except for [12] and [14], the starting points and location are very predictable and repetitive because the vehicles move according to a pre-defined schedule. The simulation studies usually select a random starting and ending location for each vehicle and it keeps on moving constantly. [10], for example, assumes that a vehicle would always choose the shortest route and start another trip without stopping.

Table 2 compares the key results found in [9,10,11,12,13,14] on the physical characteristics of traffic pattern and transmission area. Table 3 compares the same group of literature according to their key findings on network connection characteristics. For fields listed with N/A indicate the area is not explicitly examined in the corresponding study. Although some studies focus on some specialized metrics or environment more than the others, we find the key observations of all studies have similar conclusion overall.

Study	Vehicle Density	Number of lanes	Transmission Range
Artimy et al [9]	Connectivity increase as density increase but decreases when reaching a critical density level (like a traffic jam).	Multilane has greater connectivity better than 1 lane	Connectivity drops rapidly beyond transmission range.
Saha et al [10]	At least 150 nodes to stay well connected. Connectivity increase as density increase.	N/A	At least 500 meters of transmission range to stay well-connected
Wang [11]	N/A	N/A	N/A
Blum et al [12]	- Low deployment cause low density - Frequent fragmentation, rapid topology changes.	N/A	At 500 ft range, a node can reach 37% of the other nodes.
Chen et al [13]	Increase density may increase delay if there is not enough number of lanes to avoid slow moving vehicles.	Multilane road has less delay than 1 lane road in general	N/A
Jetcheva et al [14]	With 1 km transmission rage, the median node degree is 30.	N/A	N/A

Table 2: Comparisons in physical characteristics of traffic pattern and transmission area.

Study	Route Redundancy	Connection Lifetime	Number of hops (Path Length)	Routing latency
Artimy et al [9]	N/A	Probability distribution of connection lifetime resembles power law function.	Increase path length decrease connectivity	N/A
Saha et al [10]	N/A	N/A	Average of 3 hops on average in all simulated scenarios	DSR delivers 90% of packet. Average delivery latency was 18.2 ms
Wang [11]	N/A	90% of all paths have less than 50 second of connection lifetime	Increase path length decrease connectivity	N/A
Blum et al [12]	Lifetime shorten if multi-routs are needed simultaneously	Connection lifetime directly affected by driving direction and transmission range.	Small messages over 3 or 4 hops likely suffer rout errors.	N/A
Chen et al [13]	N/A	N/A	N/A	Optimistic forwarding and bi-directional traffic decrease delay
Jetcheva et al [14]	N/A	N/A	Maximum number of hops for 1.5 km transmission range is 48 hops	N/A

Table 3: Comparisons on network characteristics.

2.2. Available Technologies

The availability of various types of technologies inside a vehicle makes VANET unique. Nodes in general ad hoc network may run out of power quickly or have a lack of on-board visualization equipments. In VANET, cars and vans equipped with onboard GPS (Global Positioning System), DVD/CD player, and speaker systems are common. Commercial truck and RV often equipped with even more gadgets such as sensors and rare-view cameras. The passengers, also, are often well equipped with laptops, PDA and cellular phones with connection to the Internet.

The most popular technology that current solutions make use of is probably onboard Global Positioning System. Previously, assuming all or most nodes to be equipped with GPS for a routing protocol is not realistic. However, the popularity of GPS on vehicles makes this assumption acceptable. In section 3, we examine some routing solutions that make use of GPS extensively.

Another example of making use of available vehicle technology is the concept of integrating the technologies together for resource sharing. In [15], the authors explore the feasibility of a scenario, in which vehicles with Wireless LAN radios can use other vehicles with both Wireless LAN and Cellular radios as mobile gateways to the Internet. Their result indicates that majorities of the vehicles can connect to at least one gateway long enough for traditional applications like FTP and HTTP. The results are based on the simulation of a scenario in highway environments with a constant node density. Therefore, the effects of node exiting directly on connectivity and connection lifetime may not be reflected realistically. The study does not examine handoff issues, which is important for maintaining a stable connection even when vehicles are exiting the system.

2.3. Operating Environment

Vehicles can move into many different environments that can interfere with wireless communication. Possible environments include city environments, disaster situations, and extreme weather conditions. City environments, for example, have certain unique characteristics: (1) many tall buildings obstructing and interfering the transmission signals, (2) vehicles are closer together than in the highway scenario, thus create interference if transmission range is large, (3) the topology is usually two dimensional (e.g. Cross streets).

Most of the characterization studies we find assume a highway environment and do not include effects such as obstructions, severe interferences and weather conditions. Researchers in [16] consider scenarios in which people move at a sporting event, in a disaster area and at a conference, but not in the speed of moving vehicles. In section two, we will explore a couple routing solutions attempting to address the obstruction of tall buildings in a city environment.

2.4. Application Requirement

Understanding the application requirement, the criteria for an application to work, is a key to design successful routing strategies. Many have speculated a variety of applications ranging from safety applications to Internet E-commerce services. We categorize current works in VANET applications into two groups: (1) message and file delivery and (2) Internet connectivity.

2.4.1. Message and File Delivery

This group of research focuses on enabling the delivery of messages and files in a vehicular network to the target receivers with acceptable performance. A group of applications, such as accident and road construction warning system, require the network protocols to forward messages from a sender to only relevant receivers based on the location and driving direction. Also, safety application is time sensitive and should be given priority over non-safety application.

For example, authors in [17] envision a crashed vehicle wanting to inform the other vehicles that they are approaching the hazardous area in a road accident. Instead of broadcasting a message to the vehicles in all directions, the protocol determines the destination of the message based on the sending vehicle's location, speed, driving direction and time. In [18], the authors aim to quantify the performance of vehicle collision avoidance applications on top of VANETs. First, it states that the safety application required short response time and reliability. Non-safety applications are more delay tolerant but they compete with safety applications for the same frequency spectrum. Their simulation results indicate that DSRC provides promising latency support for time-critical safety applications but the throughput needs improvement because less than 60% of vehicles successfully receiving the message.

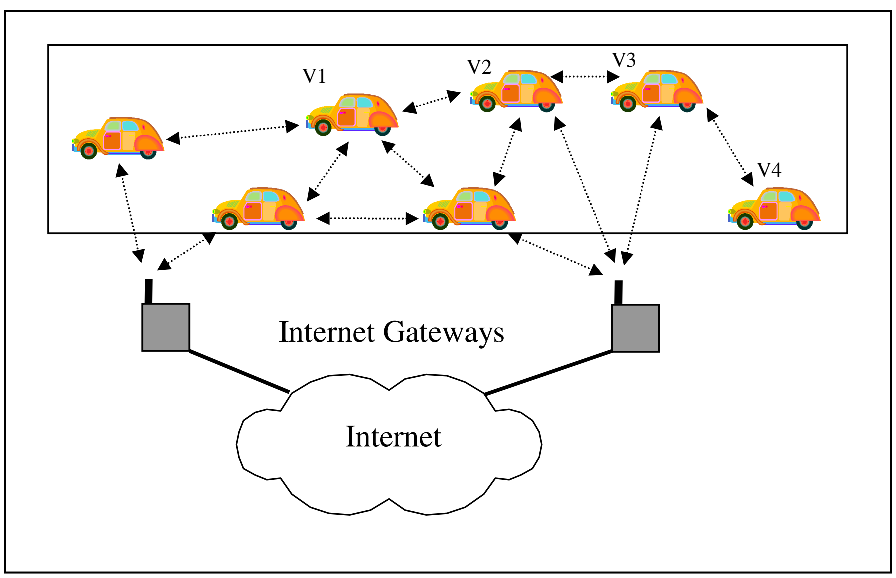

Figure 2 Future Vehicular Communication Scenario [19]

2.4.2. Internet Connectivity

This group of works focuses on connecting the vehicles to the Internet using roadside beacons and inter-vehicles communications. Authors in [19] envision a future vehicular communication scenario in which the vehicles can communicate to roadside Internet gateway via the ad hoc network as shown in figure 2. The authors point out difficulties such as the interoperability of communication protocols, mobility support, communication efficiency, the discovery of Internet Gateways, and the handover of connection from one gateway to the next need to be addressed for such a scenario. It focuses on providing a framework for discovering roadside Internet gateway and applying QoS principles in selecting the best gateway for the underlying applications.

2.5. Security and Privacy

Security and privacy issues are prominent in VANET because the networks are publicly available in any roads at any time. Hu in [20] provides a detail survey of potential security issues in wireless ad hoc routing. Privacy is also an issue. For example, in many position-based routing protocols, the location and a persistent ID of a vehicle are constantly broadcast to neighboring vehicles [5].

For example, Song in [21] points out that most of the proposed ad hoc routing protocols assume an implicit trust-your-neighbor relationship in which all the neighboring nodes behave properly. They propose a location service for position-based ad hoc routing to prevent message tampering, dropping, and location table tampering attacks by malicious or compromised users.

3. CURRENT ROUTING STRATEGIES TO ADAPT THE CHARACTERISTICS

In last section we discuss VANET characteristics including high-speed node movement, frequent topology change, and short connection lifetime especially with multi-hop paths. These three characteristics degrade the performance of some popular topological routing protocols for ad hoc network significantly. This is because topological routing needs to maintain a path from the source to the destination, but the path expires quickly due to frequent topology changes. The frequently changed topology suggests that a local routing scheme without the need to keep track of global routing information scales better in VANET. In addition, the popularity of GPS also makes position-based routing, which maintains only local information about the node's position, a popular routing strategy. A successful VANET routing solution also needs to handle issues such as sparse network density, interfering environment, long path length, latency etc. In this section, we look at the current routing proposals that address the characteristics of VANET. We select the routing strategies designed and tested on VANET simulation and categorize them into (1) position-based, (2) enhanced topological-based, and hybrid approach.

3.1. Position-based Routing

Position-based routing usually performs well in a highway environment in which nodes are moving quickly and transmission area has few obstructions.

Cluster Based Location Routing (CBLR) [22]: This algorithm assumes all vehicles can gather their positions via GPS. The algorithm divides the network into multiple clusters. Each cluster has a cluster-head and a group of members within the transmission range of the cluster-head. The cluster-head and members are formed as follow:

1. A new vehicle transmits a Hello Message.
2. If the vehicle gets a reply from the cluster-head vehicle, the new vehicle would become a member of the cluster. If not, the new vehicle becomes the cluster-head.
3. The cluster-head is responsible to send a message every second to let the members know its existence.

To reduce message flooding in the global networks, members of the cluster transmit packets to the cluster-head only and the cluster-head is responsible to forward message to other clusters. The cluster head knows the routing information within the cluster. Between the cluster-heads, at least one bridge node is needed to take care of the communication between the cluster-heads. A cluster-head must at least know one bridge node, so the packet can be send outside the cluster. The cluster-head then send message to a bridge node. The bridge node would transmit the message to another cluster-head. The paper gives examples on how to recover from the loss of member, cluster-head, or bridge node.

Simulation was used to verify the algorithm. The authors indicate that the simulations assume that transmission of packet is synchronized, which would not be the case in a real scenario. The test results show that the algorithm shows good performance when the speed of vehicles is less then 89 miles per hour (30 m/s). The end-to-end delay is 8 msec on average.

3.2. Enhanced Topological-based Routing

As mentioned, topological-based routing is believed to be less scalable in VANET environments. Su et al propose an algorithm to predict the future state of network topology and perform route reconstruction proactively [23]. Their goal is to address the problems of rapid topological changes by reconstructing a usable route rapidly. The basic idea is that connection time can be approximated if the velocities of two nodes, distance, and transmission ranges are known. The proposed equation finds the amount of time two mobile hosts will state connected using the velocity differences, moving directions, transmission range and the current distance at a given time.

3.3. Hybrid Approach

The Hybrid approach makes use of node position information and also information on the paths from the source to the destination. The algorithms with this approach usually assumes every vehicle not only has an on board GPS but also have the digital maps ready in storage. This may not be realistic during the early deployment of VANET. However, there exists location-identifying scheme without GPS or digital maps [24].

Lochert et al algorithm [25]: Lochert contributes in two areas in this paper: (1) their simulation model consider the effects of obstructions in vehicular ad hoc network, (2) they propose a routing strategy for a city environment.

A microscopic simulator Videlio, developed by DaimlerChrysler AG is used to simulate the traffic flow. A small part of the city of Berlin was modeled as a graph of streets and movement of 955 vehicles are simulated. The city obstruction is achieved by extending the simulator to consider the spaces between streets as buildings. As a result, two nodes can only communicate directly when they are in their respective transmission range and also they are within the 'line of sight' of each other. The network model is simulated using NS-2.

They propose Geographic Source Routing (GSR), which combines position and topological information in routing decision. The scheme requires an on board GPS system that contains the digital maps of current areas. The sender computes a sequence of junctions the packet has to traverse to reach the destination using the underlying map of the streets. The current implementation selects the path between source and destination by a Dijkstra's shortest path calculation based on the street map. The simulation shows GSR outperforms the topological-based algorithms, DSR and AODV, with respect to delivery rate and latency.

Cheng et al algorithm [26]: This algorithm is very similar to Lochert's algorithm above. It combines the knowledge of position and topology information from digital maps to construct a shortest route from source to the destination. Other than providing an algorithm from a source to one destination node, it enhances the algorithm to route to a destination area.

Tian et al algorithm [27]: Like the above two algorithms presented in this category, this algorithm makes use of static digital map data to construct a path from the source to the destination instead of maintaining global link information. In addition, the authors point out a situation in which a forwarding vehicle may never find a suitable neighbor because the path information is based on static map data instead of existing links. They propose three ways to recover from this situation: (1) buffer the packets and retry a number of times, (2) switch to greedy forwarding, (3) compute another path using the static map.

4. DIRECTION OF FUTURE RESEARCH

This section suggests some directions of future research for VANET in general. As seen in some of the studies presented, the transmission range of a vehicle may be too strong or too weak during certain times of the day and in certain city environments. When the transmission is too strong, it creates interference and lowers the system throughput. When transmission is too low, the vehicle cannot reach other vehicles. Smart algorithms that adjust the transmission range according to external factors can help finding the balanced transmission range. Further research is needed to provide these smart algorithms based on the characteristics of vehicular networks.

Increasing body of research makes use of GPS data in the routing proposals. The routing proposals often assume that either all nodes have GPS or none has GPS. The most realistic situation is that some nodes have GPS and some do not. We believe more works is needed to address the mixed environment.

Current studies in characterization of VANET focus mostly on a simulated highway environment. Vehicle characterization in city and other environments is less studied. Also, most of the characterization study is done with simulation. Actual field experiments to study the characterization on the vehicles moving in highways with actual network layers are potential future works. Programs and tools that can perform automatic communication and data collection in these field experiments are also valuable.

Increasing number of users owns varied kind of wireless equipments that make use of varied kind of wireless technology and protocols. Commercial vendors are adapting new wireless protocols quickly while consumers are still making use of older technologies. For example, a cellular phone may be running Bluetooth, a PDA running Wireless LAN 802.11a and the laptop using Wireless LAN 802.11b and the vehicle is potentially using yet another slightly different protocol. A mixture of old and new wireless technologies and equipments are likely to be used by the consumers. A vehicular ad hoc network that can connect these equipments and technologies together seamlessly will change the way we travel. For example, a passenger can make a telephony phone call via IP using her PDA through the vehicular ad hoc network. The routing solutions need to take care of the forwarding of different kinds of packets and routing protocols in such network.

Several studies have focused on understanding time critical safety application. The characterization of VANET indicates that delay-tolerant applications can perform well. Exploring delay tolerant application in the VANET space and the routing implication are future research topics.

5. SUMMARY

In this paper we examine VANET in two parts. First, we examine the unique characteristics of VANET. Second, we present current literature on routing strategy for vehicular ad hoc networks. We show the major characteristics of Vehicular Ad Hoc Networks in five areas: (1) mobility and network characteristics, (2) available technologies, (3) operating environments, (4) application requirements, and (5) security and privacy. For mobility and network characteristics, a detail survey and comparisons are provided. All projects that we have found simulate the network characteristics either with connectivity graphs or popular simulators. Some simulate the traffic model based on actual traffic traces while some based on hypothetical topologies. The major metrics studied include vehicle density, number of lanes, transmission range, route redundancy, connection lifetime, path length, and latency. We find the different studies agree with each other's findings.

We discuss the effects of the characteristics on existing routing protocols. Furthermore, we provide a body of representative routing mechanisms designed for the characteristics of VANET. The mechanisms are divided into (1) position-based, (2) enhanced topological-based, and (3) hybrid approach. Position-based protocols make use of position information about each node without maintaining global link information. Studies show that topological-based routing protocols do not perform well in VANET. Thus, we present an algorithm for predicting the connection lifetime so that an alternative path can be constructed rapidly. Increasing number of works use the hybrid approach. In hybrid approach, position information as well as static link information constructed from digital map is used. Finally, we suggest direction of future research.

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