Routing in Vehicular Ad Hoc Networks: A Survey

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Abstract: *Vehicular Ad Hoc Network (VANET) is an emerging new technology integrating ad hoc network, wireless LAN (WLAN) and cellular technology to achieve intelligent inter-vehicle communications and improve road traffic safety and efficiency. VANETs are distinguished from other kinds of ad hoc networks by their hybrid network architectures, node movement characteristics, and new application scenarios. Therefore, VANETs pose many unique networking research challenges, and the design of an efficient routing protocol for VANETs is very crucial. In this article, we discuss the research challenge of routing in VANETs and survey recent routing protocols and related mobility models for VANETs.*

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1. Introduction

Vehicular Ad Hoc Networks (VANETs) are emerging new technology to integrate the capabilities of new generation wireless networks to vehicles. The idea is to provide (1) ubiquitous connectivity while on the road to mobile users, who are otherwise connected to the outside world through other networks at home or at the work place, and (2) efficient vehicle-to-vehicle communications that enable the *Intelligent Transportation Systems* (ITS). Therefore, vehicular ad hoc networks are also called *Inter-vehicle Communications* (IVC) or *Vehicle-to-Vehicle* (V2V) *communications*.

ITS is the major application of VANETs. ITS includes a variety of applications such as co-operative traffic monitoring, control of traffic flows, blind crossing, prevention of collisions, nearby information services, and real-time detour routes computation. Another important

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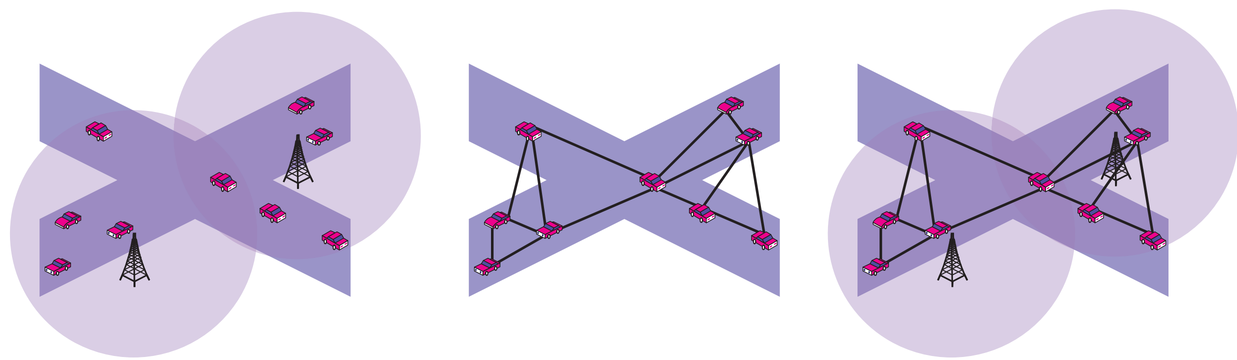

FIGURE 1 Three possible network architectures for VANETs.

application for VANETs is providing Internet connectivity to vehicular nodes while on the move, so the users can download music, send emails, or play back-seat passenger games.

VANET or IVC has drawn a significant research interests from both academia and industry. One of the earliest studies on IVC was started by JSK (Association of Electronic Technology for Automobile Traffic and Driving) of Japan in the early 1980s. Later, California PATH [1] and Chauffeur of EU [2] have also demonstrated the technique of coupling two or more vehicles together electronically to form a train. Recently, the European project CarTALK 2000 [3] tries to investigate problems related to the safe and comfortable driving based on inter-vehicle communications. Since 2002, with the rapid development of wireless technologies, the number of papers on VANET or IVC has been dramatically increased in academia. Following this trend, various new workshops were created to address research issues in this emerging area, such as *ACM International Workshop on Vehicular Ad Hoc Networks* from 2004 and *International Workshop on Intelligent Transportation* from 2003. On the other hand, several major automobile manufacturers have already begun to invest inter-vehicle networks. Audi, BMW, DaimlerChrysler, Fiat, Renault and Volkswagen have united to create a non-profit organization called *Car2Car Communication Consortium* (C2CCC) [4] which is dedicated to the objective of further increasing road traffic safety and efficiency by means of inter-vehicle communications. IEEE also formed the new IEEE 802.11p task group which focuses on providing wireless access for the vehicular environment. According to the official IEEE 802.11 work plan predictions, the formal 802.11p standard is scheduled to be published in April 2009.

Because of the high nodes mobility and unreliable channel conditions, VANET has its unique characteristics which pose many challenging research issues, such as data dissemination, data sharing, and security issues. In this article, we mainly focus on a key networking problem: routing protocol for VANETs. The main requirement of routing protocols is to achieve minimal communication time with minimum consumption of network resources. Many routing protocols have been developed for *Mobile Ad Hoc Networks* (MANETs), and some of them can be applied directly to VANETs. However, simulation results showed that they suffer from poor performances because of the characteristics of fast vehicles movement, dynamic information exchange and relative high speed of mobile nodes are different from those of MANETs. So finding and maintaining routes is a very challenging task in VANETs. In addition, a realistic mobility model is very important for both design and evaluation of routing protocols in VANETs. In this article, we will survey the most recent research progress of routing protocols and mobility models in VANETs.

2. Network Architectures and Characteristics

MANETs generally do not rely on fixed infrastructure for communication and dissemination of information. VANETs follow the same principle and apply it to the highly dynamic environment of surface transportation. As shown in Figure 1, the architecture of VANETs falls within three categories: pure cellular/WLAN, pure ad hoc, and hybrid.

VANETs may use fixed cellular gateways and WLAN access points at traffic intersections to connect to the Internet, gather traffic information or for routing purposes. The network architecture under this scenario is a pure cellular or WLAN structure as shown in Figure 1(a). VANETs can combine both cellular network and WLAN to form the networks so that a WLAN is used where an access point is available and a 3G connection otherwise.

Stationary or fixed gateways around the sides of roads could provide connectivity to mobile nodes (vehicles[‡]) but are eventually unfeasible considering the infrastructure

[‡]Hereafter, we use the terms "vehicle" and "node" interchangeably.

VANETs provide ubiquitous connectivity while on the road to mobile users, and efficient vehicle-to-vehicle communications that enable the Intelligent Transportation Systems (ITS).

costs involved. In such a scenario, all vehicles and roadside wireless devices can form a mobile ad hoc network (Figure 1(b)) to perform vehicle-to-vehicle communications and achieve certain goals, such as blind crossing (a crossing without light control).

A hybrid architecture (Figure 1(c)) of combining cellular, WLAN and ad hoc networks together has also been a possible solution for VANETs. Namboodiri *et al.* [5] proposed such a hybrid architecture which uses some vehicles with both WLAN and cellular capabilities as the gateways and mobile network routers so that vehicles with only WLAN capability can communicate with them through multi-hop links to remain connected to the world.

VANETs comprise of radio-enabled vehicles which act as mobile nodes as well as routers for other nodes. In addition to the similarities to ad hoc networks, such as short radio transmission range, self-organization and self-management, and low bandwidth, VANETs can be distinguished from other kinds of ad hoc networks as follows:

- **Highly dynamic topology.** Due to high speed of movement between vehicles, the topology of VANETs is always changing. For example, assume that the wireless transmission range of each vehicle is 250 *m*, so that there is a link between two cars if the distance between them is less than 250 *m*. In the worst case, if two cars with the speed of 60 *mph* (25 *m/sec*) are driving in opposite directions, the link will last only for at most 10 *sec*.
- **Frequently disconnected network.** Due to the same reason, the connectivity of the VANETs could also be changed frequently. Especially when the vehicle density is low, it has higher probability that the network is disconnected. In some applications, such as ubiquitous Internet access, the problem needs to be solved. However, one possible solution is to pre-deploy several relay nodes or access points along the road to keep the connectivity.
- **Sufficient energy and storage.** A common characteristic of nodes in VANETs is that nodes have ample energy and computing power (including both storage and processing), since nodes are cars instead of small handheld devices.
- **Geographical type of communication.** Compared to other networks that use unicast or multicast where the communication end points are defined by ID or group ID, the VANETs often have a new type of communication which addresses geographical areas where packets need to be forwarded (*e.g.*, in safety driving applications).
- **Mobility modelling and predication.** Due to highly mobile node movement and dynamic topology, mobility model and predication play an important role in network protocol design for VANETs. Moreover, vehicular nodes are usually constrained by prebuilt highways, roads and streets, so given the speed and the street map, the future position of the vehicle can be predicated.
- **Various communications environments.** VANETs are usually operated in two typical communications environments. In highway traffic scenarios, the environment is relatively simple and straightforward (*e.g.*, constrained one-dimensional movement); while in city conditions it becomes much more complex. The streets in a city are often separated by buildings, trees and other obstacles. Therefore, there isn't always a direct line of communications in the direction of intended data communication.
- **Hard delay constraints.** In some VANETs applications, the network does not require high data rates but has hard delay constraints. For example, in an automatic highway system, when brake event happens, the message should be transferred and arrived in a certain time to avoid car crash. In this kind of applications, instead of average delay, the maximum delay will be crucial.
- **Interaction with on-board sensors.** It is assumed that the nodes are equipped with on-board sensors to provide information which can be used to form communication links and for routing purposes. For example, GPS receivers are increasingly becoming common in cars which help to provide location information for routing purposes. It is assumed that the nodes are equipped with on-board sensors to provide information which can be used to form communication links and for routing purposes. For example, GPS receivers are increasingly becoming common in cars which help to provide location information for routing purposes.

3. Routing Protocols

Because of the dynamic nature of the mobile nodes in the network, finding and maintaining routes is very challenging in VANETs. Routing in VANETs (with pure ad hoc architectures) has been studied recently and many different protocols were proposed. We classify them into five categories as follows: ad hoc, position-based, cluster-based, broadcast, and geocast routing.

Ad Hoc Routing

As mentioned earlier, VANET and MANET share the same principle: not relying on fixed infrastructure for communication, and have many similarities, *e.g.*, self-organization, self-management, low bandwidth and short radio transmission range. Thus, most ad hoc routing protocols are still applicable, such as AODV (*Ad-hoc On-demand Distance Vector*) [6] and DSR (*Dynamic Source Routing*) [7]. AODV and DSR are designed for general purpose mobile ad hoc networks and do not maintain routes unless they are needed. Hence, they can reduce overhead, especially in scenarios with a small number of network flows.

However, VANET differs from MANET by its highly dynamic topology. A number of studies have been done to simulate and compare the performance of routing protocols in various traffic conditions in VANETs [5], [8]–[11]. The simulation results showed that most ad hoc routing protocols (*e.g.*, AODV and DSR) suffer from highly dynamic nature of node mobility because they tend to have poor route convergence and low communication throughput. In [11], AODV is evaluated with six sedan vehicles. It showed that AODV is unable to quickly find, maintain, and update long routes in a VANET. Also in their real-world experiment, because packets are excessively lost due to route failures under AODV, it is almost impossible for a TCP connection to finish its three-way handshake to establish a connection. Thus, certain modification of the existing ad hoc routing protocols to deal with highly dynamic mobility or new routing protocols need to be developed.

Namboodiri *et al.* [5] considered routing from a vehicle to a gateway vehicle which is expected to be only a few hops away. The highway scenario is highly partitioned and the probability of forming long paths is small. Thus the issue of scalability is not a problem and traditional reactive routing protocols (*e.g.*, AODV) are still considered in small scale networks with path lengths of only a few hops. However, the routes created by AODV can break very frequently due to the dynamic nature of mobility involved. To reduce the ill-effects of frequent route breakages, thus increasing routing performance, two prediction-based AODV protocols: PRAODV and PRAODVM are introduced. Namboodiri *et al.* use the speed and location information of nodes to predict the link lifetimes. PRAODV constructs a new alternate route before the end of the estimated lifetime while AODV does it until route failure happens. PRAODV-M selects the maximum predicted life time path among multiple route options instead of selecting the shortest path in AODV and PRAODV. Their simulations showed some slight improvements regarding packet delivery ratio. With overhead not being as major a concern in vehicular networks, their protocols could have great utility. However, their methods depend heavily on the accuracy of the prediction method.

In [12], AODV is modified to only forward the route requests within the *Zone of Relevance* (ZOR). The basic idea is the same as the *location-aided routing* (LAR) [13]. ZOR is usually specified as a rectangular or circular range, it is determined by the particular application [14]. For example, for the road model of the divided highway, the ZOR covers the region behind the accident on the side of the highway where the accident happens.

ITS INCLUDES A VARIETY OF APPLICATIONS SUCH AS CO-OPERATIVE TRAFFIC MONITORING, CONTROL OF TRAFFIC FLOWS, BLIND CROSSING, PREVENTION OF COLLISIONS, NEARBY INFORMATION SERVICES, AND REAL-TIME DETOUR ROUTES COMPUTATION.

Position-Based Routing

Node movement in VANETs is usually restricted in just bi-directional movements constrained along roads and streets. So routing strategies that use geographical location information obtained from street maps, traffic models or even more prevalent navigational systems on-board the vehicles make sense. This fact receives support from a number of studies that compare the performance of topology-based routing (such as AODV and DSR) against position-based routing strategies in urban as well highway traffic scenarios [8], [9]. Therefore, geographic routing (position-based routing) has been identified as a more promising routing paradigm for VANETs.

Even though vehicular nodes in a network can make use of position information in routing decisions, such algorithms still have some challenges to overcome. Most position based routing algorithms base forwarding decisions on location information. For example, greedy routing always forwards the packet to the node that is geographically closest to the destination. GPSR (*Greedy Perimeter Stateless Routing*) [15] is one of the best known position-based protocols in literature. It combined the greedy routing with face routing by using face routing to get out of the local minimum where greedy fails. It works best in a free open space scenario with evenly distributed nodes. GPSR is used to perform simulations in [9] and its results were compared to DSR in a highway scenario. It is argued that geographic routing achieves better results because there are fewer obstacles compared to city conditions and is fairly suited to network requirements. However, when applied it to city scenarios for VANETs [8], [9], [16], GPSR suffers from several problems. First, in city scenarios, greedy forwarding is often restricted because direct communications between nodes may not exist due to obstacles such as buildings and trees. Second, if apply first the planarized graph to build the routing topology and then run greedy or face routing on it, the routing performance will degrade, *i.e.*, packets need to travel a longer path with higher delays. Figure 2 is an example of disconnected VANET due to the first phase of planarization in GPSR. Third, mobility can also induce routing loops for face routing, and last, sometimes packets may get forwarded to the wrong direction leading higher delays or even network partitions.

Various techniques have been proposed to deal with these challenges. Some papers use the digital map in the navigation system to calculate a preferred route from source to destination [16]–[18]. Lochert *et al.* [16] proposed *Geographic Source Routing* (GSR) that assumes the aid of a street map in city environments. GSR essentially uses a *Reactive Location Service* (RLS) to get the destination position. The algorithm needs global knowledge of the city topology as it is provided by a static street map. Given this information, the sender determines the junctions that have to be traversed by the packet using the Dijkstra's shortest path algorithm. Forwarding between junctions is then done in a position-based fashion. By combining the geographic routing and topological knowledge from street maps, GSR proposes a promising routing strategy for VANETs in city environments. The simulation results demonstrate that GSR has better average delivery rate, smaller total bandwidth consumption, similar latency of first delivered packet with DSR and AODV.

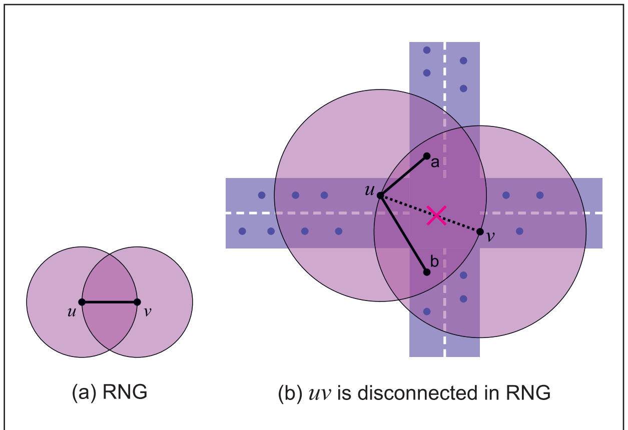

FIGURE 2 ***Example of GPSR's failure: (a)*** The relative neighborhood graph (RNG) is a planar topology used by GPSR, which consists a link *uv* if the intersection of two circles centered at *u* and *v* with radius ‖*uv*‖ (shaded area) does not contain any other nodes. ***(b)*** In GPSR, link *uv* is removed by RNG since nodes *a* and *b* are inside the intersection of two circles centered at *u* and *v*. However, due to obstacles (such as buildings), there is no direct link *ua* or *ub*. Thus the network is disconnected between *u* and *v* which causes GPSR's failure.

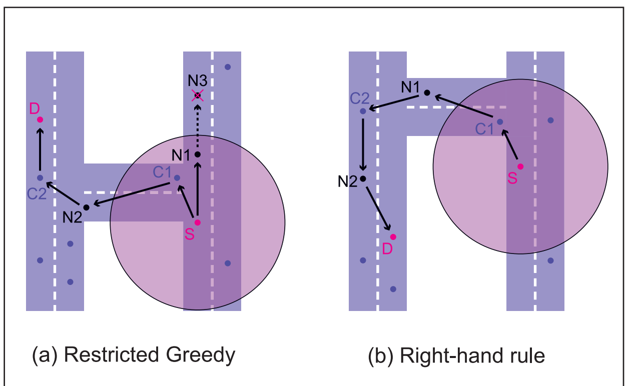

FIGURE 3 ***(a) Greedy routing vs. Restricted greedy routing in the area of a junction.*** Source S wants to forward the packet to the destination D. If a regular greedy forwarding is used, the packet will be forwarded beyond the junction (Coordinator C1) to N1, then it will be lead to a local minimum at N3. But by forwarding the packet to coordinator C1, an alternative path to the destination can be found without getting stuck in a local minimum. ***(b) Right-hand rule is used to decide which street the packet should follow in the repair strategy of GPCR.*** Node S is the local minimum since no other nodes is closer to the destination D than itself. The packet is routed to the first coordinator C1. Node C1 receives the packet and decides which street the packet should follow by the right-hand rule. It chooses the street that is the next one counter-clock wise from the street the packet has arrived on. The packet is forwarded to the next coordinator C2 through the intermediate node N1 along the street. Then the coordinator C2 decides to forward the packet to node N2. At this moment, the distance from N2 to D is closer than at the beginning of the repair strategy at node S. Hence GPCR is switched back to modified greedy routing. The packet reaches D.

Lochert *et al.* [19] also proposed another solution GPCR (*Greedy Perimeter Coordinator Routing*) later without the use of either source routing or availability of street maps. It utilizes the fact that the nodes at a junction in the street follow a natural planar graph. Thus a restricted greedy algorithm can be followed as long as the nodes are in a street. Junctions are the only places where actual routing decisions are taken. Therefore packets should always be forwarded to a node on a junction (called *Coordinator*) rather than being forwarded across the junction. See Figure 3(a) for illustration. Despite of the improved greedy routing strategy, GPCR uses a *repair strategy* to get out of the local minimum, *i.e.*, no neighbor exists which is closer to the destination than the intermediate node itself. The repair strategy (1) decides, on each junction, which street the packet should follow next (by right-hand rule) and (2) applies greedy routing, in between junctions, to reach the next junction. Figure 3(b) is an example of using the right-hand rule to decide which street the packet should follow in the repair strategy of GPCR. The simulation is done in the NS-2 simulator with a real city topology which is a part of Berlin, Germany. The authors show GPCR has higher delivery rate than GPSR with larger average number of hops and slight increase in latency.

Position-based routing for VANETs faces great challenges in a built-up city environment. Generally, vehicles are more unevenly distributed due to the fact that they tend to concentrate more on some roads than others. And their constrained mobility by the road patterns, along with more difficult signal reception due to radio obstacles such as high-rise buildings may lead VANETs unconnected. A new position-based routing technique called A-STAR (Anchor-*based Street and Traffic Aware Routing*) [8] has been proposed for such city environments. A-STAR uses the street map to compute the sequence of junctions (anchors) through which a packet must pass to reach its destination. But unlike GSR, A-STAR computes the anchor paths with traffic awareness. A-STAR differs from GSR and GPSR in two main aspects. Firstly, it incorporates traffic awareness by using statistically rated maps (counting the number of city bus routes on each street to identify anchor paths of maximum connectivity) or dynamically rated maps (dynamically monitoring the latest traffic condition to identify the best anchor paths) to identify an anchor path with high connectivity for packet delivery. Secondly, A-STAR employs a new local recovery strategy for packets routed to a local minimum that is more suitable for a city environment than the greedy approach of GSR and the perimeter-mode of GPSR. In the local recovery state, the packet is salvaged by traversing the new anchor path. To prevent other packets from traversing through the same void area, the street at which local minimum occurred is marked as "out of service" temporarily. The "out of service" streets are not used for anchor computation or re-computation during the "out of service" duration and they resume "operational" after the time out duration. With traffic awareness, A-STAR shows the best performance compared to GSR and GPSR, because it can select paths with higher connectivity for packet delivery. As much as 40% more packets are delivered by A-STAR compared to GSR.

Cluster-Based Routing

In cluster-based routing, a virtual network infrastructure must be created through the clustering of nodes in order to provide scalability. See Figure 4 for an illustration in VANETs. Each cluster can have a cluster head, which is responsible for intra- and inter-cluster coordination in the network management functions. Nodes inside a cluster communicate via direct links. Inter-cluster communication is performed via the cluster-heads. The creation of a virtual network infrastructure is crucial for the scalability of media access protocols, routing protocols, and the security infrastructure. The stable clustering of nodes is the key to create this infrastructure. Many cluster-based routing protocols [20]–[22] have been studied in MANETs. However, VANETs behave in different ways than the models that predominate in MANETs research, due to driver behavior, constraints on mobility, and high speeds. Consequently, current MANETs clustering techniques are unstable in vehicular networks. The clusters created by these techniques are too short-lived to provide scalability with low communications overhead.

Blum *et al.* [23] proposed a *Clustering for Open IVC Networks* (COIN) algorithm. Cluster head election is based on vehicular dynamics and driver intentions, instead of ID or relative mobility as in classical clustering methods. This algorithm also accommodates the oscillatory nature of inter-vehicle distances. They show that COIN produces much more stable structures in VANETs while introducing little additional overhead. COIN increases the average cluster lifetime by at least 192% and reduces number of cluster membership changes by at least 46%.

Santos *et al.* [10] presented a reactive location based routing algorithm that uses cluster-based flooding for

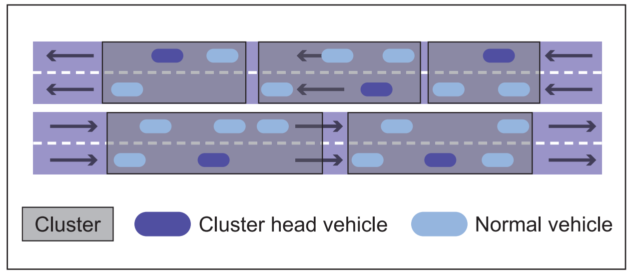

FIGURE 4 Vehicles form multiple clusters in cluster-based routing.

VANETs called LORA_CBF. Each node can be the cluster-head, gateway or cluster member. Each cluster has exactly one cluster-head. If a node is connected to more than one cluster, it is called a gateway. The cluster-head maintains information about its members and gateways. Packets are forwarded from a source to the destination by protocol similar to greedy routing. If the location of the destination is not available, the source will send out the *location request* (LREQ) packets. This phase is similar to the route discovery phase of AODV, but only the cluster-heads and gateways will disseminate the LREQ and LREP (*Location Reply*) messages. The performances of LORA_CBF, AODV and DSR are evaluated in typical urban and highway traffic scenarios. Simulation results demonstrate that network mobility and size affect the performance of AODV and DSR more significantly than LORA_CBF.

Cluster-based method has also been used in data dissemination and information propagation for VANETs, such as in [24] the authors described a cluster-based message dissemination method using opportunistic forwarding.

In summary, cluster-based routing protocols can achieve good scalability for large networks, but a significant hurdle for them in fast-changing VANET systems is the delay and overhead involved in forming and maintaining these clusters.

Broadcast Routing

Broadcast is a frequently used routing method in VANETs, such as sharing traffic, weather, emergency, road condition among vehicles, and delivering advertisements and announcements. Broadcast is also used in unicast routing protocols (routing discovery phase) to find an efficient route to the destination. When the message needs to be disseminated to the vehicles beyond the transmission range, multi-hop is used.

The simplest way to implement a broadcast service is flooding in which each node re-broadcasts messages to all of its neighbors except the one it got this message from. Flooding guarantees the message will eventually reach all nodes in the network. Flooding performs relatively well for a limited small number of nodes and is easy to be implemented. But when the number of nodes in the

NODE MOVEMENT IN VANETS IS USUALLY CONSTRAINED ALONG ROADS AND STREETS, SO ROUTING STRATEGIES THAT USE GEOGRAPHICAL LOCATION MAKE SENSE.

network increases, the performance drops quickly. The bandwidth requested for one broadcast message transmission can increase exponentially. As each node receives and broadcasts the message almost at the same time, this causes contentions and collisions, broadcast storms and high bandwidth consumption. Flooding may have a very significant overhead and selective forwarding can be used to avoid network congestion.

Durresi *et al.* [25] presented an emergency broadcast protocol, BROADCOMM, based on a hierarchical structure for a highway network. In BROADCOMM, the highway is divided into virtual cells, which moves as the vehicles move. The nodes in the highway are organized into two level of hierarchy: the first level includes all the nodes in a cell; the second level is represented by the *cell reflectors*, which are a few nodes usually located closed to the geographical center of the cell. Cell reflector behaves for a certain time interval as a base station (cluster head) that will handle the emergency messages coming from members of the same cell, or close members from neighbor cells. Besides that, the cell reflector serves as an intermediate node in the routing of emergency messages coming from its neighbor cell reflectors and decides which will be the first to be forwarded. This protocol outperforms similar flooding based routing protocols in the message broadcasting delay and routing overhead. However, it is very simple and only works with simple highway networks.

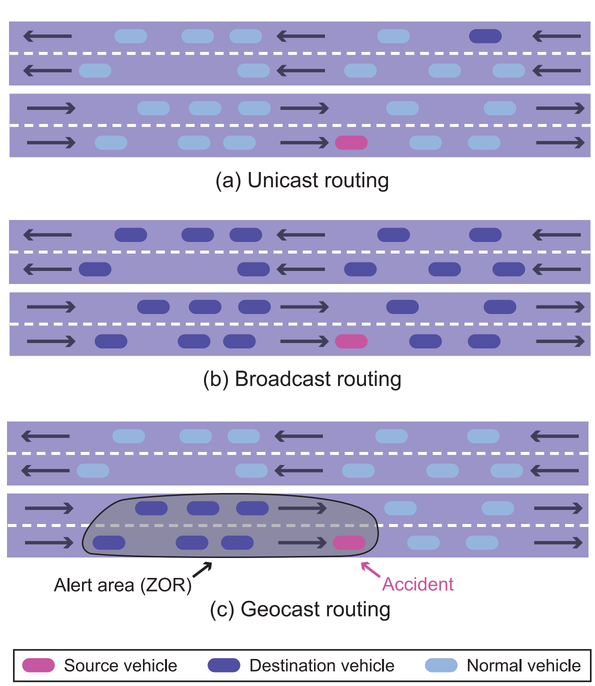

FIGURE 5 Different communication scenarios in VANETs.

Urban Multi-Hop Broadcast protocol (UMB) [26] is designed to overcome interference, packet collisions, and hidden nodes problems during message dissemination in multihop broadcast. In UMB, the sender nodes try to select the furthest node in the broadcast direction to assign the duty of forwarding and acknowledging the packet without any a priori topology information. At the intersection, repeaters are installed to forward the packets to all road segments. UMB protocol has much higher success percentage at high packet loads and vehicle traffic densities than 802.11-distance and 802.11-random protocols, which are flooding based modified IEEE 802.11 standards to avoid collisions among rebroadcast packets by forcing vehicles to wait before forwarding the packets.

Vector-based TRAcking DEtection (V-TRADE) and *History-enhanced* V-TRADE (HV-TRADE) [27] are GPS based message broadcasting protocols. The basic idea is similar to the unicast routing protocol *Zone Routing Protocol* (ZRP) [28]. Based on position and movement information, their methods classify the neighbors into different forwarding groups. For each group, only a small subset of vehicles (called border vehicles) is selected to rebroadcast the message. They show significant improvement of bandwidth utilization with slightly loss of reachability, because the new protocols pick fewer vehicles to re-broadcast the messages. But they still have routing overhead as long as the forwarding nodes are selected in every hop.

Geocast Routing

Geocast routing [29] is basically a location-based multicast routing. The objective of a geocast routing is to deliver the packet from a source node to all other nodes with a specified geographical region (*Zone of Relevance*, ZOR). Many VANET applications will benefit from geocast routing. For example, a vehicle identifies itself as crashed by vehicular sensors that detect events like airbag ignition, then it can report the accident instantly to nearby vehicles. Vehicles outside the ZOR are not alerted to avoid unnecessary and hasty reactions. In this kind of scenarios, the source node usually inside the ZOR. See Figure 5 for an illustration of difference among unicast, broadcast and geocast in VANETs.

Geocast can be implemented with a multicast service by simply defining the multicast group to be the certain geographic region. Most geocast routing methods are based on directed flooding, which tries to limit the message overhead and network congestion of simple flooding by defining a forwarding zone and restricting the flooding inside it. Non-flooding approaches (based on unicast routing) are also proposed, but inside the destination region, regional flooding may still be used even for protocols characterized as non-flooding.

In [14], a simple geocast scheme is proposed to avoid packet collisions and reduce the number of rebroadcasts. When a node receives a packet, it does not rebroadcast it immediately but has to wait some waiting time to make a decision about rebroadcast. The waiting time depends on the distance of this node to the sender. The waiting time is shorter for more distant receiver. Thus mainly nodes at the border of the reception area take part in forwarding the packet quickly. When this waiting time expires, if it does not receive the same message from another node then it will rebroadcast this message. By this way, a broadcast storm is avoided and the forwarding is optimized around the initiating vehicle. The scheme also uses a maximal-hop-number threshold to limit the scope of the flooding. Bachir and Benslimane [30] proposed a *Inter-Vehicles Geocast* protocol, called IVG, to broadcast an alarm message to all the vehicles being in risk area based on defer time algorithm in a high way. The main idea is very similar to [14].

Maihöfer and Eberhardt [31] concerned with cache scheme and distance aware neighborhood selection scheme to deal with the situation of high velocities in VANET compared to regular geocast protocols. The main idea of their cached greedy geocast inside the ZOR is to add a small cache to the routing layer that holds those packets that a node cannot forward instantly due to a local minimum. When a new neighbor comes into reach or known neighbors change their positions, the cached message can be possibly forwarded to the newly discovered node. Their distance aware neighborhood strategy takes frequent neighborhood changes into account. It chooses the closest node to destination which is inside the range *r* (smaller than the transmission range) instead of the node transmission range in the general greedy routing mode. Notice that in greedy routing, the intermediate node always select next hop node that lies close to the relaying nodes' transmission range border, so the selected next hop node has high possibility to leave the transmission range because of the high speed node movement. Simulation results show that a cache for presently unforwardable messages caused by network partitioning or unfavorable neighbors can significantly improve the geocast delivery success ratio. The improved neighborhood selection taking frequent neighborhood changes into account significantly decreases network load and decreased end-to-end delivery delay.

Beside of the classical geocast routing, recently, Maihöfer *et al*. [32] also studied a special geocast, called abiding geocast, where the packets need to delivered to all nodes that are sometime during the geocast lifetime (a certain period of time) inside the geocast destination region. Services and applications like position-based advertising, publish-and-subscribe, and many others profits from abiding geocast. In [32], the authors provided three solutions: (1) a server is used to store the geocast messages; (2) an elected node inside the geocast region stores the messages; (3) each node stores all geocast packets destined for its location and keeps the neighbor information.

A REALISTIC MOBILITY MODEL IS NOT ONLY VERY IMPORTANT FOR GETTING ACCURATE RESULTS IN ROUTING PERFORMANCE EVALUATION BUT ALSO A NECESSARY COMPONENT TO PREDICT THE NEXT POSITIONS OF VEHICLES AND MAKE SMARTER ROUTE DECISIONS.

4. Mobility Model

In this section, we will briefly review the *mobility model*§ used by VANET routing protocols. A realistic mobility model is not only very important for getting accurate results in routing performance evaluation but also a necessary component to predict the next positions of vehicles and make smarter route decisions in many VANET routing protocols. Choffnes *et al*. [33] showed protocol performance varies with the mobility models and traffic scenarios. Realistic mobility models for VANETs need to take into account street conditions, urban conditions, traffic speed, vehicle density, and obstacles such as buildings.

One of the simplest and the earliest mobility models is *Random WayPoint* (RWP) Mobility model [34], where nodes randomly choose a destination and continue to move toward that destination at a uniform speed. When the destination is reached, another destination is chosen at random and so forth. RWP is widely used in ad hoc network simulations (such as NS-2), but it does not attempt to model any real mobility situation since street-bound vehicles follows a completely different movement pattern. Nadeem *et al*. [35] modified RWP model by accepting road length, average speed, number of lanes, and average gap between vehicles as parameters.

Saha and Johnson [36] first attempted to propose a realistic street mobility model where they used the road information from the TIGER (*Topologically Integrated Geographic Encoding and Referencing*) [37] US road map by US Census Bureau. In their model, they convert the map into a graph. Then they assume that each node starts at some random point on a road segment and moves toward a random destination following shortest path algorithm.

§Some papers refer it as *traffic model,* however, to distinguish it from the network traffic model, we use *mobility model* in this article.

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The speed on each road is uniformly distributed within 5mph above and below the speed limit. A more realistic mobility model, *STreet RAndom Waypoint* (STRAW) [33] is also based on the road information from the US road map by US Census Bureau. STRAW uses a simple car-following model to simulate realistic traffic congestion in an urban environment. Compared with model in [36], STRAW considers the interaction among cars, traffic congestion and traffic controls. Both AODV and DSR are used to compare performances of STRAW against RWP under varying traffic conditions in Chicago and Boston and it is concluded that significantly different results are obtained by the use of a realistic mobility model.

A new trend of building mobility model is using the realistic vehicular trace data. Fübler *et al.* [38] used a set of movement traces derived from typical situations on German Autobahns to simulate the traffic movement on a highway. The movement of cars is defined as tuples of a one-dimensional position and a lane on the highway for discrete time steps of 0:5 seconds. They cut those movement trace data into valid portions and combine them into certain movement scenarios. Jetcheva *et al.* [39] recorded the movement traces of the buses of the public transportation system in Seattle, Washington. However, these traces only describe the movement of the buses; they represent a tiny fraction of the total number of road traffic participants. Recently, Naumov *et al.* [40] introduced a new source of realistic mobility traces for simulation of inter-vehicle networks. Their traces are obtained from a *Multi-agent Microscopic Traffic Simulator* (MMTS) [41], which is capable to simulating public and private traffic over real regional road maps of Switzerland with a high level of realism.

5. Applications and Integrations

As more and more research is being done in the area of vehicular ad hoc communications, newer applications are emerging from this technology. Most VANETs application can be categorized into two groups: intelligent transportation applications and comfort applications.

Intelligent transportation applications are the major applications of VANETs and ITS which include a variety of applications such as on-board navigation, co-operative traffic monitoring, control of traffic flows, analysis of traffic congestion on the fly and detour routes computation based on traffic conditions and the destination. For example, existing road side sensors monitor traffic density and vehicular speeds and send them to a central authority which uses them to compute traffic flow controls and optimal traffic light schedules. This kind of an extended "feedback" loop can be greatly reduced by VANETs where vehicular nodes share road conditions among themselves. In case of a road accident, the mobile nodes can even relay this information to road side sensors which then warn oncoming traffic about congestion or contact emergency response teams. VANETs can also be used for the implementation of blind crossing and highway entries to prevent collisions, and provide information query services of nearby points of interest on a given route by interacting with fixed road-side gateways, for example, upcoming gas stations or motels. These kinds of applications usually use broadcast or geocast routing schemes to exchange and distribute messages.

Comfort applications are applications to allow the passengers to communicate either with other vehicles or with Internet hosts which improve passengers' comfort. For example, VANETs provide Internet connectivity to vehicular nodes while on the move so the user can download music or play back-seat passenger games. Usually, some fixed or dynamic assigned network-to-Internet gateways are added to the networks, so they can deliver the messages between the VANET and the Internet. These applications use unicast routing as the primary communication method.

We mainly focus on routing protocols for VANETs with ad hoc architectures in this article. However, other kinds of communication technologies can also be integrated to support vehicle-to-vehicle communications. For example, integrating the new cellular networks can enhance the coverage and improve the connectivity in rural areas. Ultra-wide band communication systems can also be integrated with VANETs to provide very high data rates. The vision for future intelligent transportation systems is the support of the co-existence and interoperability of heterogeneous wireless technologies with varying requirements.

6. Conclusion

In this article, we discuss the challenges of designing routing protocols in VANETs and survey several routing protocols recently proposed for VANETs. Table 1 summarizes the characteristics of these routing protocols (*i.e.*, what are their routing types, whether and how they use position information, and whether they have hierarchical structures) and how they are evaluated (*i.e.*, simulators and simulation scenarios). In general, position-based routing and geocasting are more promising than other routing protocols for VANETs because of the geographical constrains. However, the performance of a routing protocol in VANETs depends heavily on the mobility model, the driving environment, the vehicular density, and many other facts. Therefore, having a universal routing solution for all VANETs application scenarios or a standard evaluation criterion for routing protocols in VANETs is extremely hard. In other words, for certain VANETs application, we need to design specific routing protocol and mobility model to fulfill its requirements.

Even though routing in VANETs has received more and more attention in the wireless network community recently as a relatively new area, there are still quite a few challenges that have not been carefully investigated yet. For example, security is also an important issue for routing in VANETs, because many applications will affect life-or-death decisions and illicit tampering can have devastating consequences. The characteristics of VANETs make the secure routing problem more challenging and novel than it is in other communication networks. Recently, there are some initial efforts on this topic [42], [43]. Another challenge related to routing is efficient data dissemination and data sharing in VANETs. There are several approaches are proposed [44]–[47]. Other related topics also include research on network fragmentation, delay-constrained routing, and delay-tolerant network.

THE CHARACTERISTICS OF VANETs MAKE THE SECURE ROUTING PROBLEM MORE CHALLENGING AND NOVEL THAN IT IS IN OTHER COMMUNICATION NETWORKS.

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TABLE 1 *Comparisons of routing protocols in VANETs.*

Routing Protocols	*Routing Type*	*Position Information? (How to Use)*	*Hierarchical Structure?*	*Network Simulator*	*Simulation Scenario*
AODV	Unicast	No	No	—	—
DSR	Unicast	No	No	—	—
GPSR	Unicast	Packet Forwarding	No	—	—
PRAODV/PRAODV-M [5]	Unicast	Route-Selection (lifetime prediction)	No	NS2	Simple highway model (20km segment only)
AODV-bis [12]	Unicast	Route-Req-Forwarding	No	—	—
GSR [16]	Unicast	Packet Forwarding	No	NS2	Real city model (from map)
GPCR [19]	Unicast	Packet Forwarding	No	NS2	Real city model (from map)
A-STAR [8]	Unicast	Packet Forwarding (also use traffic info.)	No	NS2	Grid city model
COIN [23]	Unicast	Cluster Formation	Yes	Own	Real highway model
LORA_CBF [10]	Unicast	Packet Forwarding (also location prediction)	Yes	OPNET	Simple circle and square road
Flooding	Broadcast	No	No	—	—
UMB [26]	Broadcast	Packet Forwarding	No	Own	Simple intersection road
V-TRADE/HV-TRADE [27]	Broadcast	Classify Forwarding Group	No	Own	Simple intersection
BROADCOMM [25]	Broadcast	Formation of Cells	Yes	Own	Simple highway model (15 nodes only)
Msg Dis Protcl [14]	Geocast	Packet Forwarding	No	Own	Simple highway model (10 km long)
IVG [30]	Geocast	Packet Forwarding	No	Glomosim	Simple highway model (10 km long, 100/200 nodes)
Cached Geocast [31]	Geocast	Packet Forwarding	No	NS2	Quadratic network (size from 1 km to 4km, 100 nodes)
Abiding Geocast [32]	Geocast	Packet Forwarding	No	—	—

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