Survey of Routing Protocols in Vehicular Ad Hoc Networks

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ABSTRACT

The chapter provides a survey of routing protocols in vehicular ad hoc networks. The routing protocols fall into two major categories of topology-based and position-based routing. The chapter discusses the advantages and disadvantages of these routing protocols, explores the motivation behind their design and trace the evolution of these routing protocols. Finally, it concludes the chapter by pointing out some open issues and possible direction of future research related to VANET routing.

INTRODUCTION

With the sharp increase of vehicles on roads in the recent years, driving has not stopped from being more challenging and dangerous. Roads are saturated, safety distance and reasonable speeds are hardly respected, and drivers often lack enough attention. Without a clear signal of improvement in the near future, leading car manufacturers decided to jointly work with national government agencies to develop solutions aimed at helping drivers on the roads by anticipating hazardous events or avoiding bad traffic areas. One of the outcomes has been a novel type of wireless access called Wireless Access for Vehicular Environment (WAVE) dedicated to vehicle-to-vehicle and vehicle-to-roadside communications. While the major objective has clearly been to improve the overall safety of vehicular traffic, promising traffic management solutions and on-board entertainment applications are also expected by the different bodies

(C2CCC[1], VII[2], CALM[3]) and projects (VICS[4] (Yamada, 1996), CarTALK 2000 (Reichardt D, 2002), NOW[5], CarNet (Morris R, 2000), FleetNet (Franz, 2001)) involved in this field.

When equipped with WAVE communication devices, cars and roadside units form a highly dynamic network called a Vehicular Ad Hoc Network (VANET), a special kind of Mobile Ad-Hoc Networks (MANETs). While safety applications mostly need local broadcast connectivity, it is expected that some emerging scenarios (Lee, 2009) developed for intelligent transportation systems (ITS) would benefit from unicast communication over a multi-hop connectivity. Moreover, it is conceivable that applications that deliver contents and disseminate useful information can flourish with the support of multi-hop connectivity in VANETs.

Although countless numbers of routing protocols (Mauve, 2001; Mehran, 2004) have been developed in MANETs, many do not apply well to VANETs. VANETs represent a particularly challenging class of MANETs. They are distributed, self-organizing communication networks formed by moving vehicles, and are thus characterized by very high node mobility and limited degrees of freedom in mobility patterns.

As shown in Figure 1, there are two categories of routing protocols: topology-based and geographic routing. Topology-based routing uses the information about links that exist in the network to perform packet forwarding. Geographic routing uses neighboring location information to perform packet forwarding. Since link information changes in a regular basis, topology-based routing suffers from routing route breaks.

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[1] Car 2 Car Communication Consortium, http://www.car-to-car.org

[2] The Vehicle Infrastructure Integration (VII) Initiative, http://www.vehicle-infrastructure.org

[3] Continuous Air Interface for Long and Medium Interface (CALM), http://www.calm.hu

[4] Vehicle Information and Communication System

[5] Network On Wheels, www.network-on-wheels.de

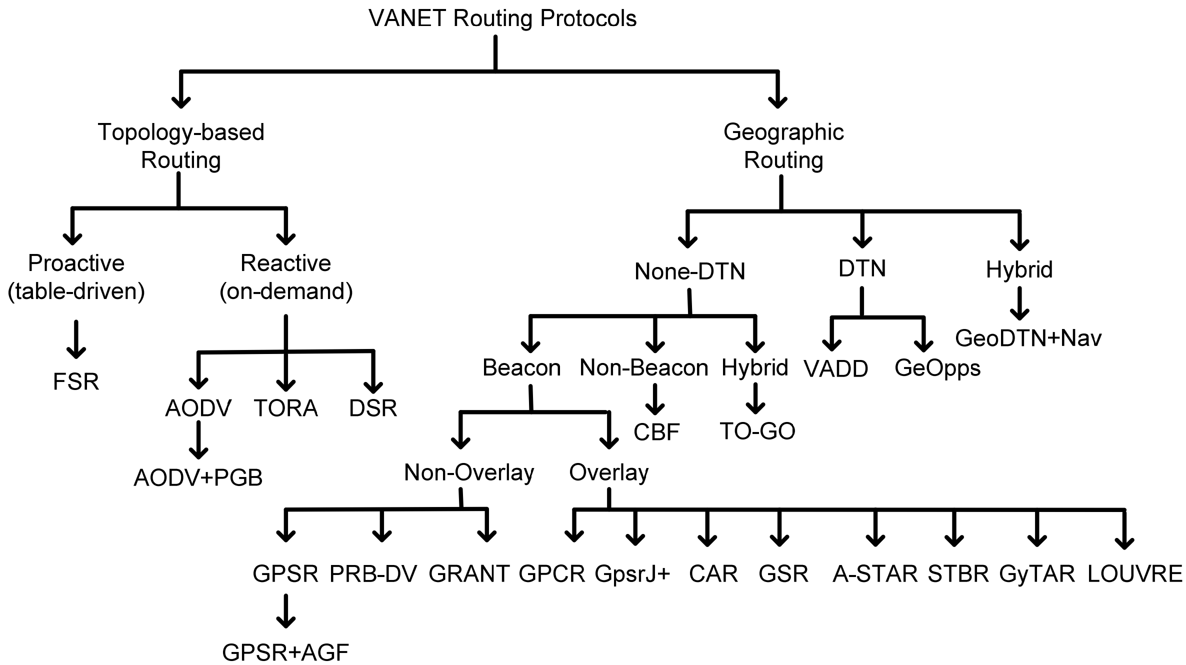

Figure 1: Taxonomy of Various Routing Protocols in VANET

Despite many surveys already published on routing protocols in MANETs (Mauve, 2001; Mehran, 2004Giordano, 2003; Stojemnovic, 2004), a survey of newly developed routing protocols specific to VANETs has long been overdue. Li et al. (2007) have made an effort to introduce VANET routing protocols, yet there is still deficiency in a thorough and comprehensive treatment on this subject. A discussion of VANET topics and applications is incomplete without detailed coverage of relevant routing protocols and their impact on overall VANET architecture. In this book chapter, we seek to provide the missing building blocks by detailing the advances in VANET routing protocols. Section III describes the VANET architecture and its characteristics. Section IV presents a survey of these protocols experimented on or tailored to VANET and their advantages and disadvantages. It will explore the motivation behind their design and trace the evolution of these routing protocols. Finally, Section V will point out some open issues and possible direction of future research, and then conclude the book chapter.

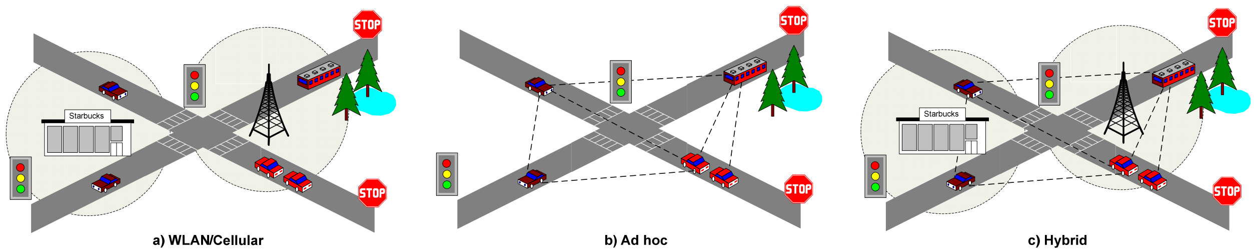

Figure 2: Three categories of VANET network architecture.

NETWORK ARCHITECTURE AND CHARACTERISTICS

According to Figure 2, the architecture of VANETs falls within three categories: pure cellular/WLAN, pure ad hoc, and hybrid. In pure cellular/WLAN architecture, the network uses cellular gateways and WLAN access points to connect to the Internet and facilitate vehicular applications. Vehicles communicate with the Internet by driving by either a cellular tower or a wireless access point.

Since the infrastructure of cellular towers and wireless access points are not necessarily widely deployed due to costs or geographic limitations, nodes may only engage in communication with each other. Information collected from sensors on a vehicle can become valuable in notifying other vehicles about traffic condition and helping the police solve crimes (Lee, 2006). The infrastructure-less network architecture is in the pure ad hoc category where nodes perform vehicle-to-vehicle communication with each other.

When there are roadside communication units such as a cellular tower and an access point and vehicles are equipped with wireless networking devices, vehicles can take advantage of the infrastructure in communicating with each other. Various applications in areas of urban monitoring, safety, driving assistance, and entertainment (Lee, 2006) have used infrastructure communicating units to access dynamic and rich information outside their network context and share this information in a peer-to-peer fashion through ad hoc, infrastructureless communication. The hybrid architecture of cellular/WLAN and ad hoc approaches provides richer contents and greater flexibility in content sharing.

Similar to mobile ad hoc networks (MANETs), nodes in VANETs self-organize and self-manage information in a distributed fashion without a centralized authority or a server dictating the communication. In this type of network, nodes engage themselves as servers and/or clients, thereby exchanging and sharing information like peers. Moreover, nodes are mobile, thus making data transmission less reliable and suboptimal. Apart from these characteristics, VANETs possess a few distinguishing characteristics, presenting itself a particular challenging class of MANETs:

Highly dynamic topology. Since vehicles are moving at *high* speed, the topology formed by VANETs is *always* changing. On highways, vehicles are moving at the speed of 60 mph (25 m/sec). Suppose the radio range between two vehicles is 250 m. Then the link between the two vehicles lasts at most 10 sec.

***Frequently* disconnected network (Intermittent connectivity)** The highly dynamic topology results in frequently disconnected network since the link between two vehicles can quickly disappear while the two nodes are transmitting information. The problem is further exacerbated by heterogeneous node density where frequently traveled roads have more cars than non-frequently traveled roads. Moreover, (non) rush hours only result in disparate node density, thus disconnectivity. A robust routing protocol needs to recognize the frequent disconnectivity and provides an alternative link quickly to ensure uninterrupted communication.

Patterned Mobility. Vehicles follow a certain mobility pattern that is a function of the underlying roads, the traffic lights, the speed limit, traffic condition, and drivers' driving behaviors. Because of the particular mobility pattern, evaluation of VANET routing protocols only makes sense from traces obtained from the pattern. There are various VANET mobility trace generators developed for the very purpose of testing VANET routing protocols in simulation. Realistic mobility traces gathered from vehicles (Jetcheva, 2003) have also been gathered for the same purpose.

Propagation Model. In VANETs, the propagation model is usually not assumed to be free space because of the presence of buildings, trees, and other vehicles. A VANET propagation model should well consider the effects of free standing objects as well as potential interference of wireless communication from other vehicles or widely deployed personal access points.

Unlimited Battery Power and Storage. Nodes in VANETs are not subject to power and storage limitation as in sensor networks, another class of ad hoc networks where nodes are mostly static. Nodes are assumed to have ample energy and computing power. Therefore, optimizing duty cycle is not as relevant as it is in sensor networks.

On-board Sensors. Nodes are assumed to be equipped with sensors to provide information useful for routing purposes. Many VANET routing protocols have assumed the availability of GPS unit from on-board Navigation system. Location information from GPS unit and speed from speedometer provides good examples for plethora of information that can possibly be obtained by sensors to be utilized to enhance routing decisions.

ROUTING PROTOCOLS

A routing protocol governs the way that two communication entities exchange information; it includes the procedure in establishing a route, decision in forwarding, and action in maintaining the route or recovering from routing failure. This section describes recent *unicast* routing protocols proposed in the literature where a single data packet is transported to the destination node without any duplication due to the overhead concern. Some of these routing protocols have been introduced in MANETs but have been used for comparison purposes or adapted to suit VANETs' unique characteristics. Because of the plethora of MANET routing protocols and surveys written on them, we will only restrict our attention to MANET routing protocols used in the VANET context. Figure 1 illustrates the taxonomy of these VANET routing protocols which can be classified as topology-based and geographic (position-based) in VANET.

Topology-based Routing Protocols
These routing protocols use links' information that exists in the network to perform packet forwarding. They can further be divided into proactive (table-driven) and reactive (on-demand) routing.

Proactive (table-driven):
Proactive routing carries the distinct feature: the routing information such as the next forwarding hop is maintained in the background regardless of communication requests. Control packets are constantly broadcast and flooded among nodes to maintain the paths or the link states between any pair of nodes even though some of paths are never used. A table is then constructed within a node such that each entry in the table indicates the next hop node toward a certain destination. The advantage of the proactive routing protocols is that there is no route discovery since route to the destination is maintained in the background and is always available upon lookup. Despite its good property of providing low latency for real-time applications, the maintenance of unused paths occupies a significant part of the available bandwidth, especially in highly mobile VANETs.

Fisheye State Routing (Iwata, 1999; Pei, 2000) is an efficient link state routing that maintains a topology map at each node and propagates link state updates with only immediate neighbors not the entire network. Furthermore, the link state information is broadcast in different frequencies for different entries depending on their hop distance to the current node. Entries that are further away are broadcast with lower frequency than ones that are closer. The reduction in broadcast overhead is traded for the imprecision in routing. However, the imprecision gets corrected as packets approach progressively closer to the destination.

Reactive (On Demand):
Reactive routing opens a route only when it is necessary for a node to communicate with another node. It maintains only the routes that are currently in use, thereby reducing the burden on the network. Reactive routings typically have a route discovery phase where query packets are flooded into the network in search of a path. The phase completes when a route is found.

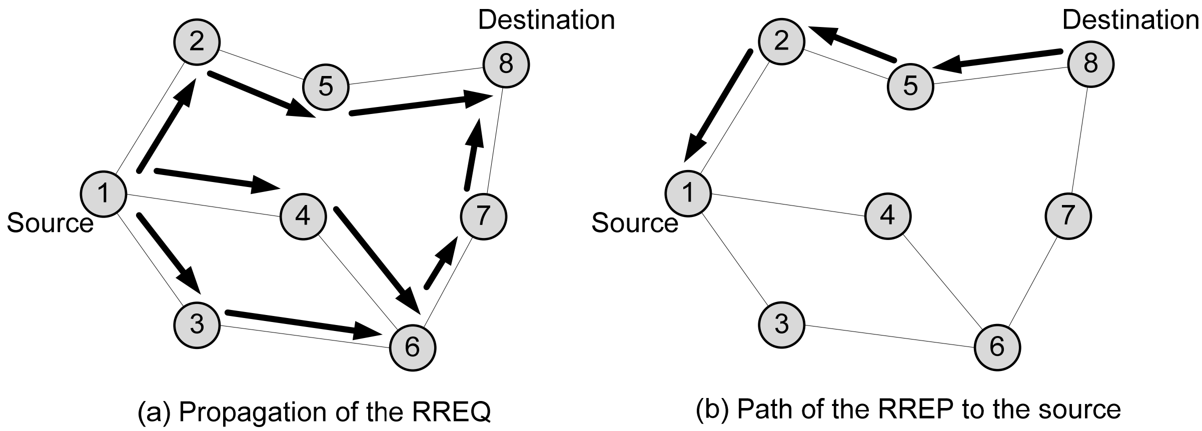

Figure 3. AODV route discovery.

AODV – In Ad Hoc On Demand Distance Vector (AODV) (Perkins, 1999) routing, upon receipt of a broadcast query (RREQ), nodes record the address of the node sending the query in their routing table (Figure 3a). This procedure of recording its previous hop is called *backward learning*. Upon arriving at the destination, a reply packet (RREP) is then sent through the complete path obtained from backward learning to the source (Figure 3b). At each stop of the path, the node would record its previous hop, thus establishing the *forward* path from the source. The flooding of query and sending of reply establish a full duplex path. After the path has been established, it is maintained as long as the source uses it. A link failure will be reported recursively to the source and will in turn trigger another query-response procedure to find a new route.

AODV+PGB – Preferred Group Broadcasting (PGB) (Naumov, 2006) is a broadcasting mechanism that aims to reduce broadcast overhead associated with AODV's route discovery and to provide route stability especially important in VANETs where fast moving vehicles are used as wireless hosts. Based on the received signal of the broadcast, receivers can determine whether they are in the preferred group and which one in the group to broadcast. Since only one node is allowed to broadcast and since the preferred group is not necessarily the one that makes the most progress towards the destination, route discovery might take longer than before. Another drawback is that broadcast can discontinue if the group is found to be empty (possibly because of sparse networks). Packet duplication can happen as two nodes in the preferred group can broadcast at the *same* time. According to Naumov et al. (2006), the way to deal with broadcast duplication is to add packet's predecessors into the packet. This creates the same type of overhead in the packet as DSR.

DSR – Dynamic Source Routing (DSR) (Johnson, 1996) uses *source routing*, that is, the source indicates in a data packet's the sequence of intermediate nodes on the routing path. In DSR, the query packet copies in its header the IDs of the intermediate nodes that it has traversed. The destination then retrieves the entire path from the query packet (a la source routing), and uses it to respond to the source. As a result, the source can establish a path to the destination. If we allow the destination to send multiple route replies, the source node may receive and store multiple routes from the destination. An alternative route can be used when some link in the current route breaks. In a network with low mobility, this is advantageous over AODV since the alternative route can be tried before DSR initiates another flood for route discovery.

There are two major differences between AODV and DSR. The first is that in AODV data packets carry the destination address, whereas in DSR, data packets carry the full routing information. This means that DSR has potentially more routing overheads than AODV. Furthermore, as the network diameter increases, the amount of overhead in the data packet will continue to increase. The second difference is that in AODV, route reply packets carry the destination address and the sequence number, whereas, in DSR, route reply packets carry the address of each node along the route.

TORA – Temporally Ordered Routing Algorithm (TORA) (Park, 2007) routing belongs to a family of link reversal routing algorithms where a directed acyclic graph (DAG) toward the destination is built based on the height of the tree rooted at the source. The directed acyclic graph directs the flow of packets and ensures reachability to all nodes. When a node has a packet to send, it broadcasts the packet. Its neighbor only broadcasts the packet if it is the sending node's downward link based on the DAG.

A node would construct the directed graph by broadcasting a query packet. Upon receiving a query packet, if a node has a downward link to the destination, it will broadcast a reply packet; otherwise, it simply drops the packet. A node, upon receiving a reply packet, will update its height only if the height from the reply packet gives the minimum of all the heights from reply packets it has received so far. It then rebroadcasts the reply packet.

The advantages of TORA are that the execution of the algorithm gives a route to *all* the nodes in the network and that it has reduced far-reaching control messages to a set of neighboring nodes. However, because it provides a route to all the nodes in the network, maintenance of these routes can be overwhelmingly heavy, especially in highly dynamic VANETs.

Evaluation of the Topology-based Routing:

Jaap et al. (2005) has evaluated AODV, DSR, FSR, and TORA in city traffic scenarios on the network simulator ns-2. The city mobility model is based on a Manhattan-like road network of eight horizontal and vertical roads. The speed of the vehicles is determined based on the Intelligent-Driver Model (IDM) where a vehicle's speed is adjusted by other surrounding vehicles and road topology such as intersections (Helbing 2002). From their simulation, it is shown that AODV has the best performance and lowest control overhead. It is followed by FSR, DSR, and then TORA. DSR suffers from a very high delay because source routes change continuously due to high mobility. Its route overhead is comparable to FSR yet higher than AODV since DSR keeps route information within the packet header. The common characteristic among all four routing protocols is that performance degrades as network densities increase, indicating their scalability problem.

Lochert et al. (2003) conducted an evaluation study of Geographic Source Routing (See Section on GSR), AODV, and DSR in a small part of a map of Berlin. The movements of 955 vehicles are simulated by the traffic flow simulator Videlio (Kronjäger, et al., 1999) that incorporates a special lane changing model. The evaluation also considers a basic form of *obstacle modeling* in the propagation model. The obstacle modeling states that spaces between streets are assumed to be buildings and, therefore, radio waves cannot propagate through them. Simulation results have shown that AODV performs better than DSR for the same reason mentioned above because large packet overhead creates a significant bandwidth overload and mobility causes frequent route breakage. However, both of the topology-based reactive routing protocols do not perform as good as GSR.

Naumov et al. (2006) compared AODV, AODV+PGB, and GPSR (see later Section for the description of GPSR). The paper obtains its mobility trace of a 250 km x 260 km area of the city of Zurich, Switzerland from Multi-agent Traffic Simulator (MTS) developed by ETH Zurich. The propagation model is probabilistic Shadowing Model that considers the non-uniform non circular behavior of radio waves due to blockage. Results indicate that AODV+PGB performs better than AODV and GPSR in all node densities because of constant broadcast overhead. Comparing AODV and GPSR alone, as density of vehicles increases in both city and highway scenarios, the packet delivery ratio of AODV decreases and becomes worse than that of GPSR; and the overhead of AODV increases and becomes higher than that of GPSR. The problem of "the high administrative load" comes from frequent route breaks due to mobility and consequent route rediscovery through flooding.

Geographic (Position-based) Routing:

In geographic (position-based) routing, the forwarding decision by a node is primarily made based on the position of a packet's destination and the position of the node's one-hop neighbors. The position of the destination is stored in the header of the packet by the source. The position of the node's one-hop neighbors is obtained by the beacons sent periodically with random jitter (to prevent collision). Nodes that are within a node's radio range will become neighbors of the node. Geographic routing assumes each node knows its location, and the sending node knows the receiving node's location by the increasing popularity of Global Position System (GPS) unit from an onboard Navigation System and the recent research on location services (Flury, 2006; Li, 2000; Yu, 2004), respectively. Since geographic routing protocols do not exchange link state information and do not maintain established routes like proactive and reactive topology-based routings do, they are more robust and promising to the highly dynamic environments like VANETs. In other words, route is determined based on the geographic location of neighboring nodes as the packet is forwarded. There is no need of link state exchange nor route setup.

Figure 1 sub-classifies Geographic routing into three categories of non-Delay Tolerant Network (non-DTN), Delay Tolerant Network (DTN), and hybrid. The non-DTN types of geographic routing protocols do not consider intermittent connectivity and are only practical in densely populated VANETs whereas DTN types of geographic routing protocols do consider disconnectivity. However, they are designed from the perspective that networks are disconnected by default. Hybrid types of geographic routing protocols combine the non-DTN and DTN routing protocols to exploit partial network connectivity. We describe these three sub-categories in the following:

Non-DTN – Overlay

The fundamental principle in the greedy approach is that a node forwards its packet to its neighbor that is closest to the destination. The forwarding strategy can fail if no neighbor is closer to the destination than the node itself. In this case, we say that the packet has reached the *local maximum* at the node since it has made the *maximum* local progress at the current node. The routing protocols in this category have their own recovery strategy to deal with such a failure.

GPSR – In Greedy Perimeter Stateless Routing (GPSR) (Karp, 2000), a node forwards a packet to an immediate neighbor which is geographically closer to the destination node. This mode of forwarding is termed *greedy mode*. When a packet reaches a local maximum, a recovery mode is used to forward a packet to a node that is closer to the destination than the node where the packet encountered the local maximum. The packet resumes forwarding in greedy mode when it reaches a node whose distance to the destination is closer than the node at the local maximum to the destination.

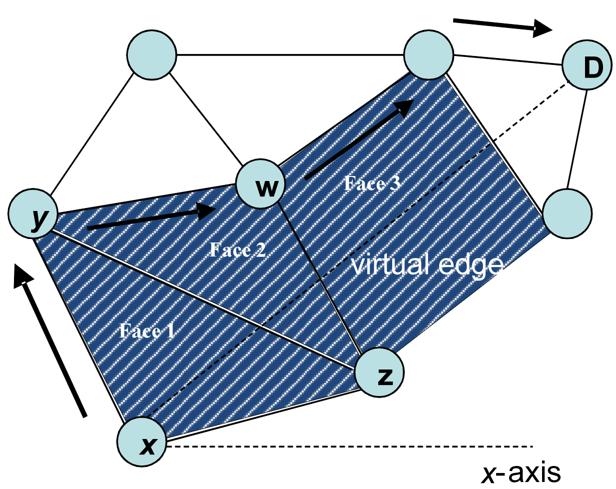

Figure 4. Right-hand rule in GPSR's perimeter mode; packet performs face routing to route along Face 1, Face 2, and Face 3 toward destination D.

GPSR recovers from a local maximum using *perimeter mode* based on the right-hand rule shown in Figure 4. The rule states that when a node *x* first enters into the recovery mode, its next forwarding hop *y* is the node that is sequentially counterclockwise to the virtual edge formed by *x* and destination *D*. Afterwards, the next hop *z* is sequentially counterclockwise to the edge formed by *y* and its previous node *x* shown in Figure 4. While walking the face, however, if the edge *yz* formed by the current node and the next hop crosses the virtual edge *xD* and results in a point that is closer than the previous intersecting point *x*, perimeter mode will perform a *face change* in that the next hop *w* is chosen sequentially counterclockwise to the edge *yz* where the closer intersecting point was found. Such routing is called *face routing* because the packet traverses many faces formed by nodes in the network until it reaches a node closer to the destination than where the packet entered in the perimeter mode and where the face routing started.

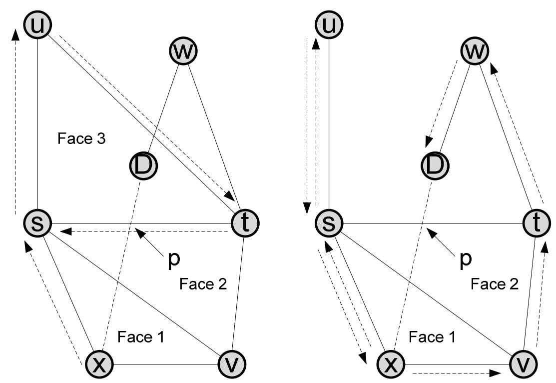

Figure 5: On the left, packet will loop around face 3; on the right, packet will eventually route to D through u, s, x, v, t, and w.

Note that if the graph is not planar, that is, there are cross edges in the graph, routing loops may occur. Consider Figure 5, *x* tries to reach *D* in perimeter mode. The packet will eventually loop around face 3 with no intersecting point closer than *p*. Had the cross edge *ut* been removed, the packet would travel the exterior face *u*, *s*, *x*, *v*, *t*, and *w* to reach *D*. Given that perimeter mode must operate on planar graphs to avoid routing loops, GPSR provided two distributed algorithms that produce Relative Neighborhood Graph (RNG) (Toussaint, 1980) and Gabriel Graph (GG) (Gabriel, 1969) which are known to be planar. Both RNG and GG algorithms yield a connected planar graph so long as the connectivity between two nodes obeys the unit graph assumption: for any two vertices, they must be connected by an edge if the distance between them is less than or equal to some threshold distance *d* and must not be connected by an edge if the distance between them is greater than *d*. However, the unit graph assumption is not true in VANETs due to channel fading (obstacles and mobility). As a result, planar graphs are usually hard to achieve in VANETs.

F¨ußler in 2002 proposed a work to compare the results in packet delivery between GPSR and DSR in the highway scenario and showed that the successfully delivered packets for DSR diminish when the communication distance becomes larger. This is due to the fact that DSR needs to maintain a route from the sender. The maintenance becomes harder when the length of the route increases. GPSR packet delivery remains at close to 100% despite larger communication distance. The topology of highway favors GPSR since local maximum rarely happens on a highway. However, results of this work established GPSR to be used in a vehicular environment.

GPSR+AGF – Naumov et al. (2006) observed two problems with GPSR in VANETs. First, due to the mobile nature of VANETs, a node's neighbor table often contains outdated information of neighbors' position. The problem can be solved by increasing beacons' frequency, yet such a solution only increases congestion and brings in potential collisions. The second problem is that the destination's location within the packet is never updated despite the destination is moving. To address these two problems, the authors proposed Advanced Greedy Forwarding (AGF) that incorporates the speed and direction of a node in the beacon packet and the total travel time, including the time to process the packet, up to the current forwarding node within the data packet. With the velocity vector, speed plus direction, each node can filter out outdated nodes in its neighbor table. With the total travel time, each forwarding node can better determine the deviation of the destination's original location and estimate its current location. Results have shown at least three times of improvement in packet delivery ratio to GPSR.

PRB-DV – Position-Based Routing with Distance Vector Recovery (PBR-DV) uses AODV-style recovery as packets fall into a local maximum. The node at the local maximum would broadcast a request packet in which is the node's position and destination's location. Upon receiving a request packet, a node would first check if it is closer to the destination than the node at the local maximum. If it is not, it records the node from which it receives the request packet (similar to backward learning) and rebroadcasts the request; otherwise, it sends a reply to the node from which it receives the request. As the reply packet travels back to the local maximum node, every intermediate node will record the previous node from which it receives the reply packet so that the local maximum node can maintain a route to a closer node than itself. The disadvantage of this scheme is that addition flooding is necessary to discover the non-greedy part of the route. There is no evaluation done comparing PRB-DV to GPSR nor AODV thus performance in packet delivery and overhead is inconclusive.

GRANT – Greedy Routing with Abstract Neighbor Table (GRANT) (Schnaufer, 2008) uses the concept of *extended greedy routing* where every node knows its *x* hop neighborhood. This gives every node a far sighted vision of the best route to take to avoid local maximum. The metric in selecting the next forwarding neighbor *E* is based on the multiplication of the distance between the node *N*, *x* hop away from *E* and the destination, the shortest path from *N* to *E*, and the charge per hop for multihop neighbors. The neighbor *E* that offers the smallest such metric will be chosen to be the next hop. Because transmitting *x*-hop neighbors in the beacon is too much overhead, GRANT separates the plane into areas and includes only one representative neighbor per area. Upon receiving a beacon, a node computes the area that the broadcasting node and its neighbors belong to, thus categorizing them into different hops from the current node.

The evaluation is based on snapshots of placement of cars from a uniform distribution. The propagation model is based on an important property of a city scenario that there are many radio obstacles such as buildings and trees. The model makes a simple assumption that nodes on different streets cannot hear each other because of radio obstacles. Results show that most of the routes in GRANT have shorter path length than traditional greedy routing. The number of times the packet is recovered per route is also less in GRANT than in traditional greedy routing. GRANT with Face routing as the recovery strategy is also compared to GRANT with Distance Vector-based recovery (similar to PRG-DV described above). The number of hops per recovery is way less in GRANT with Distance Vector-based recovery than GRANT with Face routing. Despite the disadvantage of short-range flooding, Distance Vector recovery is robust to radio obstacles that plague Face routing[6]. Since the evaluation is done on static traces and the *x*-hop neighbors are assumed to be available, the beacon overhead and possible inaccuracy are not measured and well understood. In addition, although there are more paths that have smaller path length than traditional greedy routing on a normalized percentage basis, there is no absolute performance metric such as packet delivery ratio that can validate its true performance.

Overlay:

An overlay routing has the characteristic that the routing protocol operates on a set of representative nodes *overlaid* on top of the existing network. In the urban environment, it is not hard to observe that decisions are made at junctions as these are the places where packets make turns onto a different road segment. Therefore, the overlaid routing protocols presented below have something to do with nodes at junction.

GPCR – Because nodes are highly mobile in VANETs, node planarization can become a cumbersome, inaccurate, and continuous process. In their work of Greedy Perimeter Coordinator Routing (GPCR), Lochert et al. (2005) have observed that urban street map naturally forms a planar graph such that node planarization can be completely eliminated. In this new representation of the planar graph using the underlying roads, nodes would forward as far as they can along roads in both greedy and perimeter mode and stop at junctions where decision about which next road segment to turn into can be determined. Figure 6 shows an example of GPCR forwarding where node *A* would forward packets to node *B* at a junction even though node *A*'s

[6] Radio obstacles produce asymmetric links as one node can hear the other node but the other node can hear the node. The graph produced by GG or RNG algorithm in the presence of radio obstacles is not planar.

radio range covers node *C*.

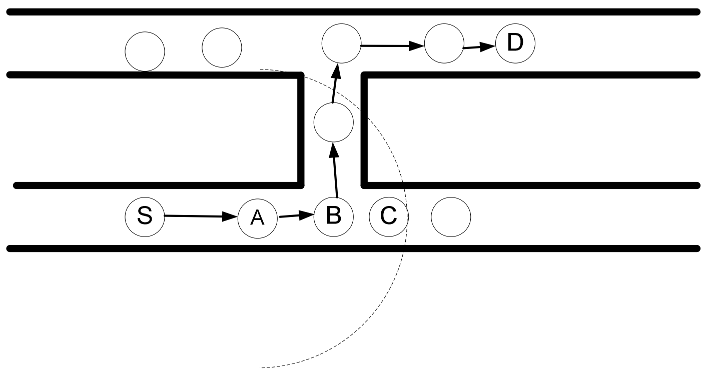

Figure 6: GPCR routing along junctions.

GPCR not only eliminates the inaccuracy of node planarization, but also improves routing performance as packets travel shorter hops in the perimeter mode. Furthermore, the improved routing decision keeps packets from being routed to the wrong direction that often leads to higher delay. GPCR does not rely on a map to determine whether a node is located at a junction, but rather provides two heuristics to determine whether a node is a junction. The first heuristic uses beacon messages and determines a node *x* is located at a junction if it has two neighbors *y* and *z* that are within the range of each other but do not list each other as neighbors. The second heuristic is derived from a *correlation coefficient* that relates a node to its neighbors. A correlation coefficient close to 0 shows there is no linear relationship between the positions of the neighbors. This indicates the node is located at a junction. Their evaluation, based on a dedicated vehicular traffic simulator, has shown that packet delivery rate does increase over GPSR.

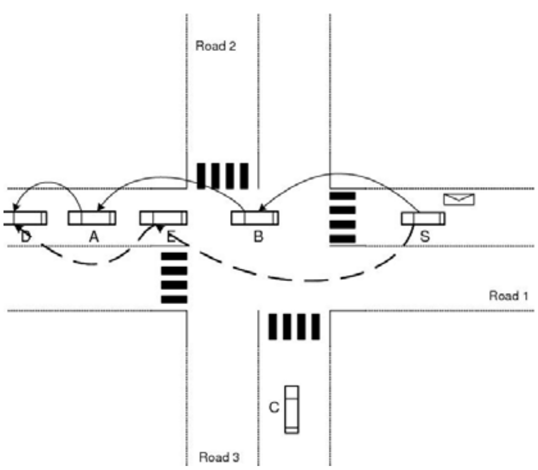

Figure 7: Dashed arrows are GpsrJ+ and solid arrows are GPCR.

GpsrJ+ – GpsrJ+ (Lee, 2007) removes the unnecessary stop at a junction while keeping the efficient planarity of topological maps. It uses two-hop neighbor beaconing to predict which road segment its neighboring junction node will take. If the prediction indicates that its neighboring junction will forward the packet onto a road with a different direction, it forwards to the junction node; otherwise, it bypasses the junction and forwards the packet to its furthest neighboring node. Figure 7 illustrates the advantage of prediction. The figure shows that GpsrJ+ can bypass the junction area and forward the packet to node *E* directly, yet GPCR forwards it to the junction node *B*, thus causing more transmissions. In the perimeter mode, GpsrJ+ uses the right-hand rule to determine the best direction (as opposed to final destination direction) and thereby the best forwarding node. That is, if the furthest node is in the same direction as the best direction, the best forwarding node is the furthest node; otherwise, the best forwarding node is a junction node. GpsrJ+ manages to increase packet delivery ratio of GPCR and reduces the number of hops in the recovery mode by 200% compared to GPSR.

CAR – Following their work on Preferred Group Broadcast (PGB) to minimize broadcast from AODV route discovery and Advanced Greedy Forwarding (AGF) to account for node mobility, Naumov et al. (2007) presented Connectivity-Aware Routing (CAR) in VANETs. CAR uses AODV-based path discovery to find routes with limited broadcast from PGB. However, nodes that form the route record neither their previous node from backward learning nor their previous node that forwards the path reply packet from the destination. Rather, *anchor points*, which are nodes near a crossing or road curve, are recorded in the path discovery packet. A node determines itself as an anchor point if its velocity vector is *not* parallel to the velocity vector of the previous node in the packet. The destination might receive multiple path discovery packets; it chooses the path that provides better connectivity and lower delays.

AGF is then used to forward the route reply back to the source via the recorded anchor points. When the source receives the route reply, it records the path to the destination and starts transmitting. Data packets are forwarded in a greedy manner toward the destination through the set of anchor points using AGF. In addition to handle mobility by AGF, CAR introduces "guards" to help to tack the current position of a destination. A guarding node can filter or redirect packets or adds information to a packet that will eventually deliver this information to the packet's destination.

The evaluation was done using a vehicular simulator and a probabilistic shadowing propagation model that uses a statistical approach to takes into account signal blockage. Results have shown CAR possesses higher packet delivery ratio (PDR) than GPSR and GPSR+AGF. The reason that CAR's PDR is higher than GPSR+AGF is that CAR guarantees to find the shortest connected path whereas GPSR+AGF may suffer from suboptimality of greedy mode in terms of finding such a path. CAR's path discovery overhead is checked by PGB. The overhead of storing guard is not in the data packets but in the beacons. According to their finding, a node on average only broadcasts 2-3 guards during the simulation. Thus, the beacon overhead is not overwhelming.

GSR – Geographic Source Routing (GSR) (Lochert et al., 2003) relies on the availability of a map and computes a Dijkstra shortest path on the overlaid graph where the vertices are junction nodes and the edges are streets that connect those vertices. The sequence of junctions establishes the route to the destination. Packets are then forwarded greedily between junctions. GSR does not consider the connectivity between two junctions; therefore, the route might not be connected through. Recovery when such a case happens is greedy forwarding. The major difference between GSR and CAR is that CAR does not use a map and it uses proactive discovery of anchor points that indicate a turn at a junction.

As mentioned above, the movements of 955 vehicles are simulated by the traffic flow simulator Videlio (Kronjäger, 1999), that incorporates a special lane changing model. The evaluation also considers a basic form of *obstacle modeling* as the propagation model. Simulation results have shown that GSR performs better than AODV and DSR in packet delivery ratio. In a densely populated network, most roads are connected that GSR forwards most of the packets. Scalability is not a problem to GSR as to AODV and DSR. However, GSR is not compared with other position-based routing protocols. Its performance in sparse networks is not verified.

A-STAR – Anchor-Based Street and Traffic Aware Routing (A-STAR) (Seet, 2004) is similar to GSR in that packets are routed through anchor points of the overlay. However, A-STAR is traffic aware: the traffic on the road determines whether the anchor points of the road will be considered in the shortest path. A-STAR routes based on two kinds of overlaid maps: a statically rated map and a dynamically rated map. A statistically rated map is a graph that displays bus routes that typically imply stable amount of traffic. Dijkstra paths computed over the statistically rated map are in general connected because of the extra knowledge. A dynamically rated map is a map that is generated based on the real-time traffic condition on the roads. Road-side deployment units can monitor the city traffic condition and distribute this information to every vehicle. Thus, the difference between a statically rated map and a dynamically rated map is accuracy of road traffic; while a statically rated map is based on bus routes that typically have high traffic volume, a dynamically rated map is based on the traffic monitored dynamically by road-side units.

A-STAR also proposes a different recovery algorithm when the packet gets stuck due to disconnectivity of the current path to the destination. The node will recompute a new anchor path and the road segment where the packet is currently located will be marked as “out of service” temporarily to prevent other packets from entering into the same problem. The notification of “out of service” is piggybacked in the recovered packets. Nodes that receive the recovered packets update their map and recomputed anchor paths accordingly.

The mobility model and propagation model are based on the M-Grid mobility model, a variant of the Manhattan model that considers not only the vehicular movement in a typical metropolis where streets are set out on a grid pattern but also the radio obstacles. A-STAR is compared to GSR and GPSR. Its packet delivery ratio is lower than GSR and GPSR with or without recovery as A-STAR can select paths with higher connectivity.

STBR – Street Topology Based Routing (STAR) (Forderer, 2005) went further than A-STAR by computing the road connectivity at junction nodes. One of the nodes at a junction is selected as a master that is responsible for checking if links to the next junctions are up or down. Within the broadcast from every master, there is also link information to all neighboring links. This is because every master will receive every other master's link information. Thus, every master contains a two-level junction neighbor table. The first level is through neighboring links to its direct junction nodes. The second level is its direct junction nodes through their neighboring links to their own junction nodes. In STBR, packets are routed based on their geographic distance to the street where the destination is on. This is different from GSR or A-STAR where routes are computed through Dijkstra shortest path.

GyTAR – Greedy Traffic Aware Routing protocol (GyTAR) (Jerbi, 2007) is an overlaid approach similar to the approaches mentioned above in that packets are forwarded greedily toward the next junction which will then determine the best junction to forward next. GyTAR assumes that the number of cars is given per each road from roadside units and determines the connectivity of roads. A score is given to each neighboring junction considering the *traffic density* and their *distance* to the destination. The weights to traffic density and their distance to the destination are configurable parameters. GyTAR tries to mimic the shortest path routing by taking into account the road connectivity.

Simulations are based on a 2500m x 2000m map of 100 to 300 nodes. The movement of cars is adapted to the mobility model from (Davis, et al., 2001). GSR is compared to GyTAR which shows better packet delivery ratio. However, since it is not compared to any other overlaid routing protocol in this category, it is hard to gauge its relative performance.

LOUVRE – Lee et al. (2008) has summarized geographic greedy overlay routing into two camps. The first camp is geo-reactive overlay routing where the next overlaid node is determined based on their neighboring nodes' distance to the destination (STBR) or a combination of it and traffic density (GyTAR). The second camp is geo-proactive overlay routing where the sequence of overlaid nodes is determined a-priori (GSR and A-STAR). Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE) belongs to the second camp. It takes note of the fact that above a given vehicular density threshold, an overlay link remains connected regardless of the vehicular spatio-temporal distribution on the link. Thus, by only considering overlay links based on such density threshold when establishing overlay routes, most routes would partially use the same overlay links. With these considerations, geo-proactive overlay routing becomes attractive as it guarantees global route optimality and reduces the delay for establishing overlay routes. The drawback of this approach is obviously its scalability.

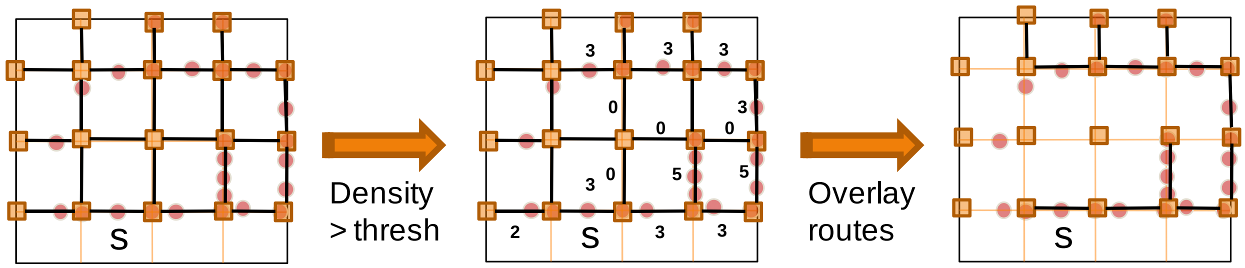

Figure 8: Procedure in obtaining routes to nodes from S. Density threshold is 3 in the pictorial example.

Figure 8 shows the procedure in which LOUVRE obtains routes to nodes from node *S*. From the peer-to-peer density scheme, LOURVE first filters out roads that do not have density over the threshold, determined by the road length and radio range. Then the overlaid routes are built on top of roads whose density is above the threshold. This forms the graph the Dijkstra shortest path algorithm runs on. The algorithm automatically obtains the shortest path between *S* and its destination.

The novelty of LOUVRE is that road density which correlates to road connectivity is computed in a peer-to-peer fashion to remove reliance on deployment of roadside units. Thus, each node has the density of all the "connected" roads in the network. The Dijkstra shortest path is then built by roads with density above a certain density threshold, correlating closely to road connectivity. Simulation is conducted based on VanetMobisim (Härri, 2008), an open source and freely available realistic vehicular traffic generator for network simulators and simple road blocking propagation model. LOUVRE performs better than GPCR and GPSR due to LOUVRE's global knowledge of the density distribution on road segments and on local maxima, typical information that is not available to GPSR and GPCR. The hop count and delay are also significantly reduced as LOUVRE does rarely encounter local maxima and therefore mostly does not use a recovery mode.

CBF:

Contention-Based Forwarding (CBF) (F¨ußler et al., 2004) is a geographic routing protocol that does not require proactive transmission of beacon messages. Data packets are broadcast to all direct neighbors and the neighbors decide if they should forward the packet. The actual forwarder is selected by a distributed timer-based contention process which allows the most-suitable node to forward the packet and to suppress other potential forwarders. Receivers of the broadcast data would compare their distance to the destination to the last hop's distance to the destination. The bigger the difference, the larger is the progress and shorter is the timer.

CBF is compared with GPSR with the perimeter mode disabled and with beacons of different intervals using realistic movement patterns of vehicles on a highway. With beacon interval of 0.25 seconds (the lowest set in the experiment), the packet delivery ratio (PDR) of GPSR is still not as good as that of CBF. As the beacon interval increases (up to 2 seconds), its PDR drops. (Please revise) Evaluation also shows that as the communication distance and thus the number of hops a packet has to travel increases, the load on the wireless medium increases more for GPSR than CBF due to GPSR's constant beaconing overhead.

Hybrid:

TOpology-assist Geo-Opportunistic Routing (TO-GO) (Lee et al., 2009) is a geographic routing protocol that exploits topology knowledge acquired via 2-hop beaconing to select the best target forwarder and incorporates opportunistic forwarding with the best chance to reach it. It is different from CBF in three main aspects. First, rather than picking the next forwarding node that makes the best progress to the destination, it picks the next forwarding node that makes the best progress to a target node. A target node is defined to be the node that greedy algorithm or recovery algorithm would normally pick except at the junction where optimization in choosing the target node either beyond the junction or at the junction is based upon whether the routing is in greedy mode or recovery mode. The reason for choosing the target node instead of the destination as the frame of reference is to take care of the city topology where roads intersect and destination usually does not lie on the same street as the source as in the highway. Packets have to make multiple turns into different streets before arriving at the destination. The data is then broadcast to all direct neighbors. Whoever's distance is closer to the target node gets picked to be the next forwarding node.

The second difference is that unlike CBF, there is still the need of beacons, which are used for nodes to pick the target node. The fact that the data is broadcast and only the node that makes the furthest progress toward the target is chosen is to account for wireless channel errors and low packet delivery rate arising from multi-path fading, shadowing, and mobility – the furthest node (the target node) usually does not receive the data packet. Packets are therefore "opportunistically" making their best progress toward the target node and thus the destination. TO-GO uses a novel way to choose the forwarding set of nodes that are candidates for the next forwarding node. The set is chosen so that all nodes can hear one another (no hidden terminals) and make a progress toward the target node.

Lastly, TO-GO differs from CBF by providing routing decision for recovery. CBF on the highway works because the destination is always straight ahead. Thus, local maximum never occurs on the highway. Thus, the selection of the next forwarding node is always one that's closest to the destination. However, in city environments, streets cross each other and destination does not lie on the same street as the source. Thus, local maximum frequently occurs. TO-GO adapts the concept of CBF that packets are opportunistically sent to the target node, calculated by the routing decision in both the greedy and recovery mode.

Simulation results compare GPSR, GPCR, GpsrJ+, and TO-GO using mobility traces generated from VanetMobisim and road blocking propagation model. The first result shows TO-GO's performance comparable to GpsrJ+ while GPSR and GPCR lag behind in error-free channel scenario. In the error-prone channel scenario, as the channel error increases, TO-GO's packet delivery rate stays stably high while GpsrJ+'s decreases, showing the power of opportunistic forwarding.

DTN:

There are vehicular routing protocols designed for VANETs which are treated as a form of Delay Tolerant Network (DTN). Since nodes are highly mobile, in this type of a network, they suffer from frequent disconnections. To overcome this, packet delivery is augmented by allowing nodes to store the packets when there is no contact with other nodes, to carry the packets for some distance until meeting with other nodes, and to forward based on some metric on nodes' neighbors (called carry-and-forward strategy). The notable DTN vehicular routing protocols are VADD and GeOpps described below.

VADD – Vehicle-Assisted Data Delivery (VADD) (Zhao et al., 2006) is a vehicular routing strategy aimed at improving routing in disconnected vehicular networks by the idea of carry-and-forward based on the use of predictable vehicle mobility. A vehicle makes a decision at a junction and selects the next forwarding *path* with the smallest packet delivery delay. A path is simply a branched road from an intersection. The expected packet delivery delay of a path can be modeled and expressed by parameters such as road density, average vehicle velocity, and the road distance. The minimum delay can be solved by a set of linear system equations.

Zhao et. al. have introduced variations of VADD that chooses the next forwarding node after the next forwarding path has been determined. Location First Probe (L-VADD) would select a node closest to the next forwarding path even though such a node is going away from the forwarding path. Direction First Probe (D-VADD) would select a node which is going toward the forwarding path even though such a node might be further from the forwarding path than other nodes on the path. Multi-Path Direction First Probe (MD-VADD) would select multiple nodes going toward the forwarding path so as not to miss forwarding to a node that offers a shorter time to the destination. Finally, Hybrid Probe (H-VADD) combines L-VADD and D-VADD so the long packet delay from D-VADD is offset by L-VADD and routing loops from L-VADD are masked by D-VADD. Results comparing with GPSR plus buffer and various versions of VADD show that H-VADD has the best performance.

GeOpps – Geographical Opportunistic Routing (GeOpps) (Leontiadis, 2007) takes advantage of the suggested routes of vehicles' navigation system to select vehicles that are likely to move closer to the final destination of a packet. It calculates the shortest distance from packet's destination to the nearest point (NP) of vehicles' path, and estimates the arrival of time of a packet to destination. Figure 9 shows Node *A* in computing the NP of its neighbors *N1* and *N2*. Since N2 offers closer NP to the destination, Node *A* picks *N1* to forward its packets.

During the travel of vehicles, if there is another vehicle that has a shorter estimated arrival time, the packet will be forwarded to that vehicle. The process repeats until the packet reaches destination. The minimum delay used by VADD is indirectly obtained by selecting the next forwarding node whose path's nearest point is closest to the destination. GeOpps requires navigation information to be exposed to the network, thus, privacy such as vehicle's whereabouts might be an issue.

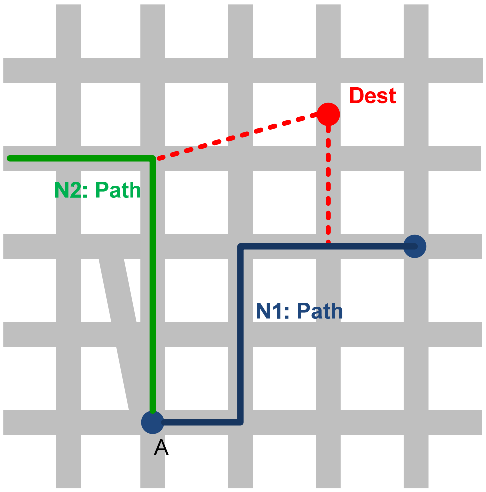

Figure 9: Calculation of the Nearest Point (NP) from packet's Destination (D) for N1 and N2.

Hybrid:

GeoDTN+Nav (Cheng et al., 2008) is a hybrid of non-DTN and DTN approach that includes the greedy mode, the perimeter mode, and the DTN mode. It switches from non-DTN mode to DTN mode by estimating the connectivity of the network based on the number of hops a packet has travelled so far, neighbor's delivery quality, and neighbor's direction with respect to the destination. The delivery quality of neighbors is obtained through *Virtual Navigation Interface* (VNI) which abstracts information from underlying hardware (e.g., Navigation System, EDR, etc.) shown in Figure 10 and provides necessary information for GeoDTN+Nav to determine its routing mode and forwarder. In addition to its hybrid approach, VNI offers users the option to protect their private data and at the same time provides best-effort routing decision.

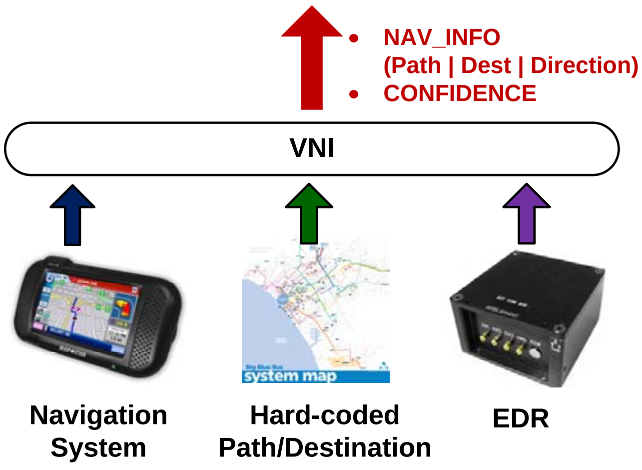

Figure 10: Virtual Navigation Interface

Cheng et al. compared GeoDTN+Nav with RandDTN, a *pure* DTN routing protocol that works as follows. At each beacon interval, a node forwards the packet that it is carrying with probability *p*. When *p* = 0, RandDTN is reduced to direct transmission scheme where packets reach the destination only when the source node meets the destination node. When *p* = 1, a node always considers its neighbors to forward the packet. To avoid the packet from being forwarded to any node, thus reducing progress towards the destination, a node would forward to its neighbor whose final destination is closest to the destination of the packet. If such a neighbor does not exist, the node would simply store and carry the packet waiting for the next beacon interval. The mobility trace is generated from VanetMobisim and the propagation model is road blocking model.

The result in a partitioned network shows that RandDTN achieves slightly better PDR and lower latency than GeoDTN+Nav. This illustrates the adaptive nature of GeoDTN+Nav in that it is able to recognize the partitioned network and quickly switch to DTN mode. RandDTN's slightly better PDR is due to the fact that GeoDTN+Nav tries to switch back to geographic routing whenever possible. However, in such a sparse network, GeoDTN+Nav is likely to fall back to DTN mode again. This increases the latency and also decreases the PDR. If the environment is tipped toward non-DTN network, however, GeoDTN+Nav will yield more favorable performance.

CONCLUSION

Table 1 summarizes the characteristics of representative routing protocols that have either been used or designed specifically for VANETs. The type and sub-types indicate whether they are topology-based or position-based and whether they are proactive/reactive, DTN or Non-DTN, overlay or not. The overhead describes the control packets associated with the successful operation of the protocols. Finally, the mobility model and propagation model present simulation settings used for protocol evaluation.

There is a plethora of VANET routing protocols. Most are designed to handle a special condition or a special problem. For example, GeOpps is designed for a special condition where VANET is assumed to be sparse and disconnected most of the time. CAR is designed for a specific problem where nodes obtain an inaccurate list of their neighbors and an inaccurate location of their destinations due to mobility. Some like TO-GO and GeoDTN+Nav address the special condition or problem by considering the hybrid approach. In TO-GO, for example, beacons are used to obtain the target node, and opportunistic forwarding is used to solve neighbor list inaccuracy. In GeoDTN+Nav, three types of modes are offered to enable nodes to determine the connectedness of the network and thus route packets in the timely manner by either the DTN or non-DTN mode.

Despite the special condition or problem that these routing protocols are considering or addressing, there is no agreed-upon standard or benchmark to validate their performance. The benchmark not only includes a standard routing protocol, but also a simulation environment. It is clear that GPSR is taken to be a widely-accepted benchmark. However, as position-based routing keeps advancing into many subareas (such as overlay, DTN, etc.) in VANETs, evaluation using GPSR is no longer a fair comparison. Furthermore, there is neither a widely-accepted mobility trace nor a propagation model used to evaluate these protocols[7]. Mobility traces can be either obtained from a close-to-reality traffic simulator or from actual traces. Because of the accessibility and limitation[8] of these traces, most evaluations use a mobility simulator. Yet, specifications about these simulator parameters are mostly non-standard. Because of the differences in simulator implementation, some parameters cannot directly be translated over. The propagation model in urban environments has recently been caught with much attention. Most of the work thus far has based their propagation model on simple road blocking model or sophisticated analytical model. Because of the lack of understanding for the right values to plug in for these sophisticated models, most have shunned away from using them.

In summary, the open issue in VANET routing is then whether there is any benchmark tool for evaluating these protocols. The research direction is that as VANET routings are advancing and becoming mature, many of the underlying assumptions and technologies will need to become mature as well so that much validity can be given to the benefits of these routing protocols.

[7] Two-ray fading model from the authors' opinion is a good model. Yet, it is not widely recognized and commonly used.

[8] The limitation of the realistic traces comes from the fact that roadside units are not widely populated and traces are collected from specific types of vehicles (like buses) following specific routes.

Routing Protocol	Type	Sub-Types	Overhead	Mobility Model	Propagation Model
FSR	Topology-based	Proactive	*All* link states	IDM on Manhattan Grid	Unknown
AODV	Topology-based	Reactive	Path states	IDM on Manhattan Grid, Videlio, MTS	Road blocking, Probabilistic shadowing
AODV+PGB	Topology-based	Reactive	Path states	MTS	Probabilistic shadowing
DSR	Topology-based	Reactive	Path states	IDM on Manhattan Grid, Videlio	Road blocking
TORA	Topology-based	Reactive	Path states	IDM on Manhattan Grid	Unknown
GPSR	Position-based	Non-DTN, Non-Overlay	Beacons	MTS	Probabilistic shadowing
GPSR+AGF	Position-based	Non-DTN, Non-Overlay	Beacons	MTS	Probabilistic shadowing
PRB-DV	Position-based	Non-DTN, Non-Overlay	Beacons and path states	Unknown	Unknown
GRANT	Position-based	Non-DTN, Non-Overlay	Two-hop beacons	Static trace from a uniform distribution	Road blocking
GPCR	Position-based	Non-DTN, Non-Overlay	Beacons	VanetMobisim	Road blocking
GpsrJ+	Position-based	Non-DTN, Overlay	Beacons	VanetMobisim	Road blocking
CAR	Position-based	Non-DTN, Overlay	Path states and beacons	MTS	Probabilistic shadowing
GSR	Position-based	Non-DTN, Overlay	Beacons	Videlio, M-Grid moblity	Road blocking
A-STAR	Position-based	Non-DTN, Overlay	Beacons	M-Grid mobility	Road blocking
STBR	Position-based	Non-DTN, Overlay	Beacons	Unknown	Unknown

GyTAR	Position-based	Non-DTN, Overlay	Beacons	Proprietory	Free space
LOUVRE	Position-based	Non-DTN, Overlay	Beacons	VanetMobisim	Road blocking
CBF	Position-based	Non-DTN, Non-Beacon	Data boradcast	Random way point	Two-Ray ground propagation model
TO-GO	Position-based	Non-DTN, Hybrid	Beacons and data broadcast	VanetMobisim	Road blocking
VADD	Position-based	DTN	Beacons	Unknown	Unknown
GeOpps	Position-based	DTN	Beacons	MTS	None
GeoDTN+Nav	Position-based	Hybrid	Beacons	VanetMobisim	Road blocking

Table 1. Summary of VANET routing protocols.

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