Spatially Aware Packet Routing for Mobile Ad Hoc Inter-Vehicle Radio Networks

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***Abstract*— Inter-Vehicle Communication will become an important building block for ITS telematics applications like safety and warning functions. Mobile ad hoc networks (MANETs) can serve as a local wireless network for exchanging information between cars for cooperative driver assistance applications. For the routing of data packets in such large-scale MANETs consisting of vehicles on the road, geographic multi-hop packet forwarding is a promising approach. However, a main drawback is that it performs poorly in networks with many topology holes. In this paper, we propose a spatially aware packet routing approach to predict permanent topology holes caused by spatial constraints and avoid them aforehand. This approach is generic and can be used in combination with any existing geographic forwarding protocol as an extension. Our simulations demonstrate that spatial awareness can significantly improve geographic forwarding performance in situations with many permanent topology holes, like in dynamic vehicle networks.**

***Index Terms*— inter-vehicle communication, ad hoc routing, spatial awareness.**

I. INTRODUCTION

For Intelligent Transportation Systems (ITS) the use of information and communication technologies in vehicles allows to extend the perception horizon of the driver by including sensor, traffic, and environment data from other vehicles travelling on the road. The goal is to develop a versatile communication platform for inter-vehicle communications based on self organizing, mobile ad hoc networks (MANETs) [1] with neither the need of preinstalled infrastructures nor the involvement of network operators. Such a mobile wireless ad hoc network will enable a localized and hence fast data exchange between vehicles for innovative active safety applications.

European telematics research projects like ”CarTALK 2000” [2] or national projects like ”FleetNet - Internet on the Road” [3] investigate the use of mobile ad hoc networks to build an inter-vehicle communication system and to develop cooperative driver assistance applications.

In order to achieve a good functionality of the driver assistance functions, like hazard warning or adaptive cruise control, even at low equipment rates of the communication system, we assume a wireless radio system with a transmission range of several hundred meters, rather than a point-to-point link between two adjacent cars. Furthermore we assume that the vehicles are aware of their geographic position, i.e. are equipped with a GPS receiver or a navigation system.

An important feature to realize the desired driver assistance and safety functions is a position-based approach for multi-hop message forwarding and addressing. By this geographic routing of data packets it is possible that for example a vehicle detecting an icy bridge sends a warning message to the road segment behind, which is relayed by intermediate cars and received by vehicles approaching the incident.

In this paper, we investigate an extension of classical position-based packet routing protocols for MANETs to improve their performance when used in inter-vehicle networks.

In contrast to topology-based routing [11], position-based routing [4], [5] relies on vehicles' geographic position to forward data packets. Depending on the packet forwarding strategy, position-based routing can be classified into *limited flooding* and *geographic forwarding* approaches. The basic idea of limited flooding is to flood data packets within a restricted geographic region or direction range, such as LAR [6] and DREAM [7]. In contrast, geographic forwarding forwards the packet to only one neighbor each time, which is successively closer to the packet's destination, such as MFR [8] and GPSR [9].

Position-based routing is based on *localized* algorithms, which achieve global objectives through purely local behaviors. Each host makes packet forwarding decisions only based on the location of itself, its neighboring hosts, and the destination. Since position-based routing is based on purely local decisions, it avoids the overhead of maintaining information about the global dynamic network topology. However, position-based routing requires *location services* for distribution and query position information among hosts.

Designing a scalable, distributed location service for mobile ad hoc networks is a highly complex task and is out of scope of our paper. In this paper we assume that source vehicles can obtain the approximate position of destination vehicles from an ad hoc location service, for example the Grid Location service (*GLS*) [10].

Although geographic forwarding can achieve high packet

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delivery rates in dense networks, it performs poorly in networks with frequent topology holes. We use the term of *topology hole* to define the situation when a data packet reaches a host that does not have any neighbor closer than itself to the destination. Thus, the geographic forwarding will fail in case of a topology hole. Depending on their life time, topology holes can be classified as *transient* or *permanent*. Transient holes are normally caused by the host mobility and only exist for a short period of time. In contrast, spatial constraints such as roads can cause permanent topology holes, which are well-predictable with knowledge about the spatial environment.

To recover from geographic routing failures, the method of planar graph face traversal is often used, e.g. in GPSR. The basic idea is to dynamically construct a planar graph of mobile hosts and deliver data packets to the destination along the graph edges, which allows temporally forwarding data packets to hosts that are further to the destination.

However, two main problems remain unsolved:

1) Since geographic forwarding is stateless, as long as a topology hole exists, each packet reaching it will initiate a routing recovery process. Frequent recovery can seriously degrade packet routing performance.
2) Planar graph face traversal requires strictly identical radio ranges for graph constructions, thus is generally not applicable in real systems, where obstacles and interference drastically modify radio ranges.

In this paper, we define a general spatial model for the geographic environment of vehicular ad hoc networks. We then propose a novel geographic forwarding protocol that makes use of spatial model to predict and avoid forwarding failures due to permanent topology holes.

The remainder of the paper is organized as follows: Section II describes the importance of spatial awareness for geographic forwarding protocols. The spatially aware packet routing algorithms are introduced in Section III. Section IV presents simulation results and finally Section V concludes the paper.

II. Motivation

In this section, we show that frequent packet forwarding failures caused by permanent topology holes can be avoided by using spatial environment information in packet routing. The routing algorithms that make use of such information are called *spatially aware routing*.

Position-based routing usually assumes that physically close hosts are also close in the network topology. Based on this assumption, data packets are forwarded repeatedly to the neighbor that is geographically closest to the packet destination until the destination is reached.

However, the assumption described above often does not hold true in vehicular ad hoc networks, where the vehicles' geographical distribution is strongly restricted by the underlying road infrastructures.

Fig. 1 shows an example of spatial awareness for geographic forwarding. On the left is a mobile ad hoc network consisting of vehicles driving on the road. The circle indicates the radio range, which is assumed to be consistent in this scenario. Assume that each vehicle knows the location information of itself, the neighboring vehicles in its radio range, and the destination vehicle.

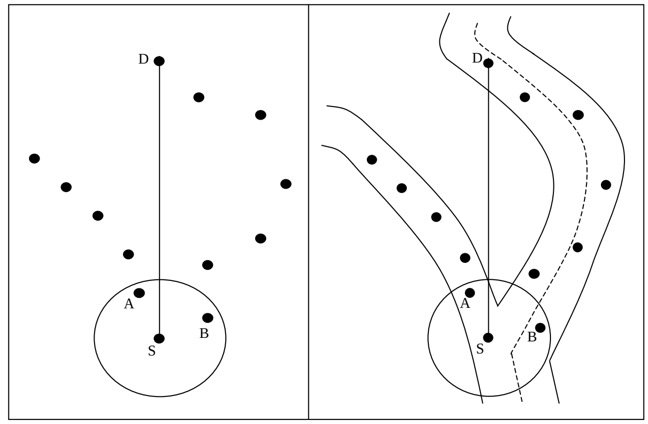

Fig. 1. The use of spatial awareness for geographic forwarding.

Source vehicle S wants to send a data packet to destination vehicle D. Using geographic forwarding, vehicle S will forward the packet to its neighbor A, which is closer to the destination than B. Without taking into account the spatial environment, this seems to be an optimal local decision. However, as the right side of Fig. 1 reveals, the vehicles' distribution is strictly bounded to the underlying road structure. Since vehicle A is actually located on the left road segment, the packet will be greedily forwarded for potentially many hops (as long as there exists a neighbor closer to the destination), before a greedy failure is recognized and eventually recovered. If the only path to the destination is on the road segment to the right, the packet has to be forwarded back and goes through vehicle B. Because a greedy failure will not be memorized in stateless routing such as GPSR, the forwarding of each subsequent packet may fail in the same way and has to be recovered each time. However, with spatial awareness, vehicle S can avoid the forwarding failure in this situation by forwarding packets to the more suitable neighboring vehicle B instead of A.

As permanent topology holes are normal in road networks, we believe that a *proactive* solution is more efficient than passive recovery solutions. We have shown that spatial awareness is very helpful to predicate permanent topology holes and avoid routing failures in advance. In the next section, we will present the routing algorithms that make use of spatial awareness.

III. Spatially Aware Routing

In this section we first introduce our spatial model and then describe the routing algorithms based on the spatial model.

A. Spatial Model

In general, a spatial model describes the spatial environment where mobile hosts are located in. The purpose of a spatial model is to provide common high-level abstractions of spatial objects and their relationships [14].

As the example in Fig. 1 shows, a vehicle can obtain a rough global view of the network topology with a simple spatial model representing the underlying road topology. Unlike the topology of mobile ad hoc networks, which is highly dynamic, the topology of the road networks rarely changes, and thus can be considered as *constant* with respect to ad hoc communications between vehicles.

To construct a spatial model, the relevant spatial information has to be *extracted* form available Geographic Information Systems (GIS), such as digital road maps used in vehicle navigation systems.

We have developed a parser [15] for the *Geographic Data Files* (GDF) [16], the European standard that is used to describe and transfer road networks and road related data. Using this parser, road topology information can be extracted from a digital road map in GDF format. Similarly, we can also build parsers for geographic data in any other formats, such as *Geographic Markup Language* (GML) [17], which is an XML-based geographic description language specified by the OpenGIS Consortium.

Our spatial model is constructed based on the extracted topology information, which is internally represented as a *graph* $G(E, V)$ consists of a set V of *vertices* referring to *significant places* together with a set E of *edges* denoting the *interconnections between places*. Hence, vehicles moving from one place to another place can be considered as moving from one *vertex* to another *vertex* along *edges* in the *graph* model. Moreover, the *weight* of edges can be used to represent different *characteristics* of interconnections, such as the physical length, average vehicle density, average speed, etc. In previous work [18], we introduced a *graph-based mobility model* to describe the vehicles' movement in spatially constrained situations based on a graph model.

An appropriate *partition* and *level of detail* can be selected to reduce the storage capacity requirements of the spatial model. For example, a big geographic area can be partitioned into a number of segments. Furthermore, a layered format of the spatial model can be used. For instance, a spatial model of roads can be put into three levels:

1) Layer 1: represents only major roads and intersections,
2) Layer 2: represents the complete street-level topology including minor roads,
3) Layer 3: represents additional semantic information, like speed limit, number of lanes, etc.

Depending on the storage capacity and application requirements, each vehicle can choose the level of detail that is needed. These methods effectively restrict the storage overhead of the spatial model.

Since the spatial model may be sometimes not locally available, some approaches can be used to obtain it from external sources: such as hoarding from infrastructures [13] or exchanging between vehicles on a peer-to-peer basis.

B. Routing Algorithms

This section describes the Spatially Aware Routing (SAR) algorithms, which consists of Geographic Source Routes (GSR) and the GSR-based packet forwarding.

1) Geographic Source Routes (GSR): A *graph* spatial model $G(E, V)$ consists of a set V of *vertices* together with a set E of *edges*. Each vertex $v = \{ID, x, y\}$ consists of its ID and its geographical coordinates (x, y). Each edge $e = \{v1, v2\}$ is defined by the vertices on its two ends. We assume the graph model to be connected, i.e. there exists at least one path from any vertex to any other vertex of the graph. The *weight function* $w(e)$ for $e \in E$ is dependent on the application, such as geographic length or the average travel time.

The source vehicle s can map itself and the destination vehicle d into the spatial model, and calculate the *shortest path* P to the destination with a shortest path algorithm, for instance, the Dijkstra algorithm. Source s then sets the *Geographic Source Route* (GSR) to P, which consists of a list of intermediate vertices. The GSR will be embedded into the header of all data packets sent by the source vehicle.

The complexity of Dijkstra algorithm for computation of the shortest path between any two vertices of the graph is $O(n^2)$, where $n = |V|$ is the total number of vertices in the graph. Since aforementioned methods like *partition* and *level of detail* are used to keep a minimum of n in the graph, the processing overhead of GSR is effectively restricted.

DSR [12] also uses a *source route* for packet forwarding. The major difference is that source routes in DSR are based on the intermediate *hops* instead of *geographic locations*. In general, GSR has the following two advantages compared to DSR:

- While DSR requires a route discovery process that broadcasts Route Request packets, GSR can be obtained from the local spatial model.
- DSR is vulnerable to the mobility of hosts and must be reconstructed whenever a link on the route is broken. In contrast, GSR is static and thus is mobility independent.

2) GSR-based Forwarding: All data packets are marked with the location of the source and the destination vehicle, as well as a GSR, which contains a list of vertices the packet must be forwarded along.

Instead of forwarding packets to the neighbor which is geographically closest to the destination, in SAR each forwarding vehicle maps the positions of its neighbors into the graph model, and chooses the neighbor with the *shortest path along the GSR* to the destination as the next hop. After a vertex in the GSR is reached (i.e. the forwarding vehicle finds the vertex to be located within its radio range), this vertex will be removed from the GSR and the packet will be forwarded to the next vertex of the GSR. With this approach, a packet will move successively closer to the destination along the GSR from one vertex to the next vertex.

However, there is a main drawback of SAR: since the GSR is based on static geographic locations instead of existing links, there is not guarantee that a forwarding vehicle can always find a suitable neighbor on the GSR. To recover from such a situation, one of the following alternative methods can be used:

- *Suspend the packet*: the forwarding vehicle can choose to suspend the packet delivery by putting it into a *suspension* *buffer* with limited storage space. Packets in the buffer are then periodically checked and forwarded again if possible. Packets that can not be forwarded will be dropped if the suspension buffer is full or after staying in the buffer for a fixed time.

- *Switch to greedy forwarding*: the forwarding vehicle can remove the GSR from the header of the packet and forward it greedily to the destination. Another option would be to retain the GSR in the packet header and switch it back to GSR-based forwarding if possible.
- *Recompute the GSR*: the forwarding vehicle can compute an alternative GSR from its current location to the destination, and replace the original GSR in the packet header with the new one. The packet will then be forwarded along the new GSR.

Source vehicle s has a packet p to send to the destination d: s computes the shortest path $P(s,d)$ and sets it to the GSR, which is then embedded into the packet header of p.

Forwarding vehicle f receives the packet p:
N is the neighbor list of f.
f maps its neighbors into the graph model.
if $\exists n \in N$ with the shortest distance along the GSR to d **then**
  f forwards p to n
else
  if recovery mechanism available **then**
    f switches p to a recovery mode
  else if recovery mechanism not available **then**
    f drops p
  end if
end if

Fig. 2. Pseudo code of basic forwarding operations in SAR.

IV. SIMULATIONS

To evaluate the proposed approach, we simulated it with the *ns-2* simulator [19] with the CMU wireless extension. Two versions have been implemented: the basic SAR protocol without a recovery method, and SARB with a suspension buffer, which can store up to 80 packets for a maximum time of 30 seconds. We compare the performance of SAR and SARB with one of the existing geographic forwarding protocols GPSR.

A section of the city of Stuttgart with an area of about 2500 m $\times$ 1800 m is modelled in the simulation (Fig. 3). A graph-based spatial model is used, which consists of 54 vertices representing significant places and 59 edges referring to road segments interconnecting them. The size of this spatial model is only 2 KB, thus we assume the model to be available in all vehicles.

We use a graph-based mobility model to simulate the vehicles moving in the city: all vehicles are initiated at randomly selected vertices and move along the edges of the graph during the simulation. Each vehicle chooses another vertex as destination randomly, and moves along the shortest path along the graph edges to it at a speed randomly chosen in a range from 30 km/h to 60 km/h. After reaching the destination vertex, the vehicle makes a pause of 10 to 30 seconds, and then moves to another randomly selected vertex. Each vehicle repeats this behavior for the duration of the simulation run.

In all simulations, the number of vehicles is fixed to 100, with the radio range varying from 50 m to 250 m to get different vehicle densities. Each simulation lasts for 900 seconds of simulation time. We simulate 20 Constant Bit Rate (CBR) traffic flows with sources and receivers chosen randomly. Each CBR flow sends at 2 Kbps, with a packet size of 64 byte. The IEEE 802.11 Medium Access Control (MAC) protocol is used, which implements the Distributed Coordination Function (DCF). All the key parameters of our simulations are shown in TABLE I.

A distributed location service is needed for both GPSR and SAR. Since our goal is to compare the performance of routing protocols without bounding to a certain location service implementation, an idealized location service is used in the simulation: each source vehicle marks packets it originates with the true location of the destination. As a result, the processing and communication overhead of the location service is not included in the simulation results. However, since the location service overhead is constant and independent of the routing implementation, this does not affect our comparisons. In general, as more and more mobile applications are requiring location services, they can be assumed to be available at the vehicle anyway.

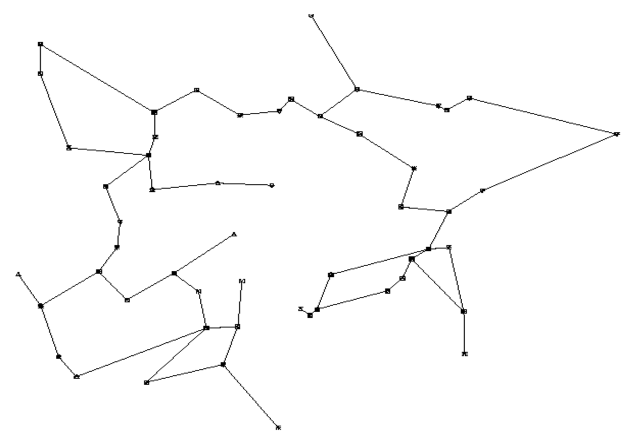

Fig. 3. The spatial model graph used in the simulation.

Following metrics are used to evaluate the simulation results:

- *Packet delivery ratio*: The fraction of originated data packets that are successfully delivered to their destination vehicles.
- *Packet delivery delay*: The average delay between originating a data packet until the packet is delivered to its ultimate destination. The packet delivery delay is only measured for packets that are successfully delivered to their destination.
- *Average hop count*: The average number of hops over which a packet has to be routed before reaching its

Parameter	Value
Total simulation time	900 s
Total number of vehicles	100
Simulation area	2500 m × 1800 m
Transmission range	50 - 250 m
Movement speed	30 km/h - 60 km/h
Pause time	10 - 30 s
Traffic type	CBR
Packet rate	2 kbps
Packet size	64 bytes
Number of connections	20

TABLE I
SIMULATION PARAMETERS

ultimate destination.

- *Average data packet size*: The average number of bytes of data packets, including the size of any routing headers added to them. The overhead of location service is not included, as an idealized location service is used in the simulation.

We simulated SAR, SARB and GPSR at each radio range with six different randomly generated movement patterns, and present the mean of each metric over these six runs. A detailed analysis of the simulation results is given in the following.

A. Packet delivery ratio

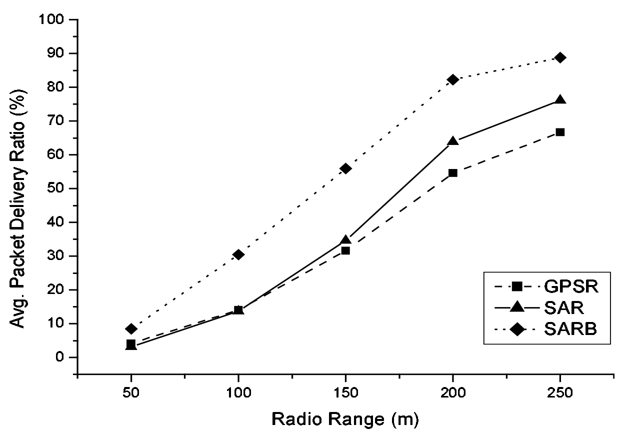

Fig. 4. Packet Delivery Ratio

As shown in Fig. 4, SAR achieves a packet delivery ratio similar to GPSR with the radio range less than 100 m, while making a relative improvement of over 15% than GPSR with larger radio ranges. This is because SAR may fail frequently and drop a large number of packets (no buffer is used) with a low vehicle density, while GPSR can switch to the perimeter mode when no closer neighbor exists. As the radio range increases, SAR can deliver significantly more packets than GPSR, whose performance is seriously degraded by permanent topology holes.

In general, SARB has a much higher delivery ratio than both SAR (up to 32% relative improvement) and GPSR (up to 51% relative improvement) in all scenarios, which shows that even a simple suspension buffer can effectively improve the performance of SAR.

B. Packet delivery delay

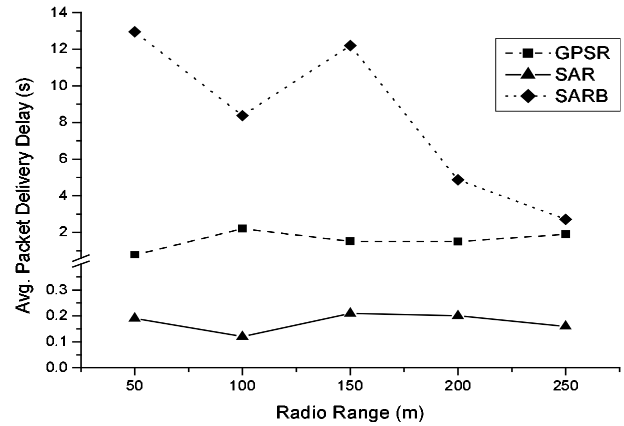

Fig. 5. Packet Delivery Delay

As shown in Fig. 5, SAR achieves a much lower delivery delay than GPSR in all scenarios. This is because SAR does not use any recovery method and a packet will be dropped immediately if can not be forwarded. In contrast, GPSR switches to perimeter mode and starts a graph traversal towards the destination if a greedy forwarding fails.

SARB presents a tradeoff between packet delivery and delivery delay, which can be observed by its obviously higher delay due to the suspension buffer. However, with larger radio ranges, the average buffer time of packets is reduced with higher vehicle densities: SARB delivers 25% more packets than GPSR with only a slightly higher delivery delay at the radio range of 250 m.

C. Average hop count

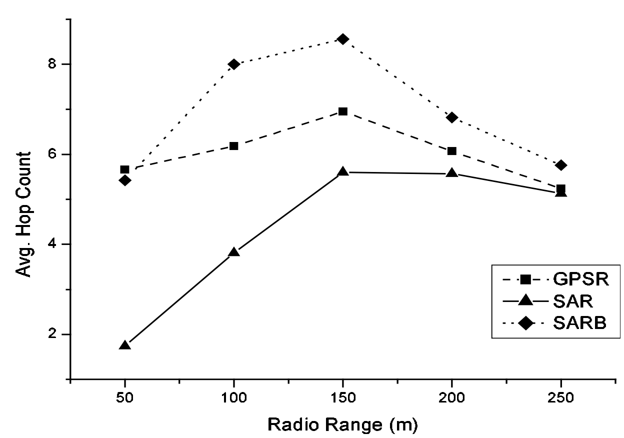

Fig. 6. Average hop count

Fig. 6 shows the number of hops of the delivered packets for all three protocols. All of them first increase with larger radio range, since more and more packets for remote destinations get delivered with an increasing vehicle density. With even larger radio ranges, the average hop count decreases again for all protocols. This indicates that less hops will be needed to deliver packets with even higher vehicle density.

SARB presents a higher number of hops because of its suspension buffer: packets are frequently suspended and forwarded, which increases the packets' hop count each time. SAR shows a much lower hop count than GPSR with radio ranges less than 150 m, with a similar delivery ratio at the same time. This indicates that with low vehicle densities GPSR delivers most of packets with perimeter mode, while SAR can deliver packets more directly by avoiding topology holes.

D. Average data packet size

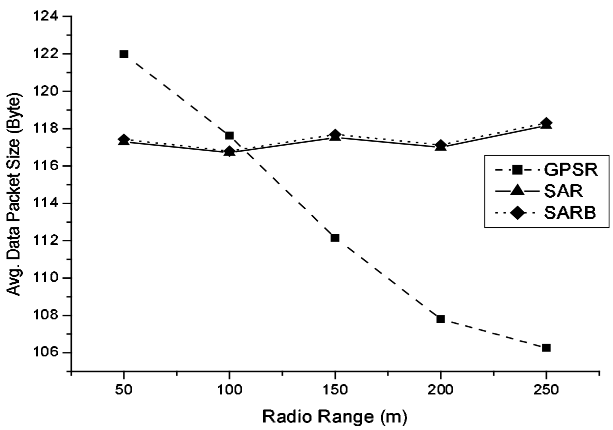

Fig. 7. Average data packet size

Fig. 7 shows the average data packet size of all the three protocols. Each packet of the CBR traffic carries 64 bytes of data payload, making the basic packet size including an IP header 84 bytes.

Each entry of the GSR corresponds to an vertex in the graph, and requires 2 bytes to store its ID. Thus the routing overhead of SAR and SARB is proportional to the number of vertices in the GSR. Since the communication patterns and spatial model are identical for all radio ranges, the data packet size of SAR and SARB is nearly constant.

The data packet size of GPSR depends on its forwarding mode: perimeter mode requires 20 bytes more overhead per packet than greedy mode. As the radio range increases, GPSR achieves an decreasing routing overhead per packet because of the reduced use of perimeter forwarding.

V. CONCLUSIONS

We motivated the use of a wireless mobile ad hoc network (MANET) to build an inter-vehicle communication system. These multi-hop networks consisting of vehicles on the road allow to locally exchange vehicle, traffic, and environment data to realize novel cooperative driver assistance applications and safety functions. The routing of data packets (i.e. the addressing and forwarding of messages) inside such an inter-vehicle radio network is performed best by a position-based routing protocol. However, most existing position-based routing protocols do not take into account the spatial environment of the ad hoc network and its impact on the mobile nodes' (or vehicles) geographic distribution. In this paper, we presented Spatially Aware Routing (SAR), a new routing approach that makes use of spatial awareness for packet forwarding. Relevant spatial information, like the road network topology is extracted from existing geographic databases, like digital maps, to generate a simple graph-based spatial model. Based on the spatial model, a source node can predict static topology holes caused by spatial constraints, like road geometry and layout of the road network. The sender then selects a Geographic Source Route to avoid these holes in packet forwarding. Our simulation results show that basic SAR can effectively improve routing performance in situations with permanent topology holes. Since an idealized location service is used in our simulations, the storage and communication overhead of location service is not included in the results. We plan to include realistic location service implementations in our simulation later, to compare the performance with topology-based routing protocols like DSR. We also intend to experiment other recovery methods, such as switching to greedy forwarding, or recomputing the GSR.

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