A Universal Geocast Scheme for Vehicular Ad Hoc Networks

Mohammad Nekoui and Hossein Pishro-Nik
University of Massachusetts, Amherst

***Abstract*—A universal communications scheme for Vehicular Ad hoc Networks (VANETs) is proposed. This scheme accounts for a diverse variety of VANET-specific characteristics such as the gradual introduction of technology, highly dynamic topology, road-constrained vehicle movement and the presence of obstacles. The scheme incorporates a geometrical framework previously proposed by the authors which makes it appropriate for urban as well as rural area deployments. Moreover, by making the scheme probabilistic, capacity-delay tradeoffs crucial for safety message exchange are addressed. Although the presence of infrastructure is a privilege to our scheme, the network can still operate in a pure ad hoc manner. Simulation results confirm that our heuristic method dramatically improves the probability of reception of nodes in different scenarios.**

***Index Terms*—Vehicular Ad Hoc Networks (VANETs), Dedicated Short Range Communications (DSRC), Geometry-aware communications.**

I. Introduction

The allocation of 75 MHz in the 5.9 GHz band for Dedicated Short Range Communications (DSRC) [1] is proposed by the FCC to improve safety and efficiency in transportation networks. This was further complemented by the introduction of the Vehicle Infrastructure Integration (VII) initiative by the US Department of Transportation [2]. VII proposes to use DSRC to establish vehicle-vehicle and vehicle-roadside communications to deliver timely information to save lives, reduce congestion, and improve quality of life. The VII Initiative envisions that each future vehicle will be equipped with an On-Board Equipment (OBE) which includes a DSRC transceiver, a Global Positioning System (GPS) receiver, and a computer. Also equipped with similar devices, Roadside Equipment (RSE) will be deployed at selected roadside locations. Therefore, vehicles will be able to communicate with each other and with the roadside by means of DSRC. The 75 MHz frequency band allocated to DSRC is divided into seven 10 MHz wide channels. These channels are either utilized by the infrastructure to deliver *infotainment* to vehicles (*service channels*) or by the vehicles to exchange crucial safety related information, where the latter is mainly carried out in the *control channel*.

It has previously been seen by the authors that vehicle-to-vehicle communications, through which vehicles gain information on each other's status, greatly benefits safety and efficiency in transportation networks [3]. There has been a plethora of studies considering the exchange of safety related information between vehicles in the literature [4, 5]. Here, the inter-vehicular communications is *geocast* by nature, where each vehicle periodically broadcasts its status packets to all other vehicles that reside within a predefined range of its vicinity. This range is referred to as the *geocast range* hereafter. The Media Access Control (MAC) protocol anticipated for DSRC communications is a variation of the conventional CSMA/CA scheme proposed for IEEE 802.11 communications [6]. However, due to the short length of the safety message payload and the broadcast nature of communications, the 4-way handshake anticipated by the standard is not efficient here. Forgoing RTS/CTS and ACK message exchanges gives rise to the *hidden node* problem, increasing the probability of packet collisions. Note that the highly dynamic topology of VANETs requires appropriate topology-transparent protocols [7]. Topology-transparent protocols are ones which do not need a detailed description of the network topology in order to schedule packet transmissions. Repetition-based protocols not only exhibit topology-transparent properties, but also seek to combat collisions with that of the hidden nodes'. In [5], the authors repeatedly transmit packets within randomly selected time slots in the current frame. In order to reduce collisions, [8] proposes predetermined transmission patterns for each node. Here, nodes are allocated minimally correlated codewords that indicate the specific time slots assigned to each as their retransmission opportunities. Although the latter algorithm is shown to perform better in case of lower traffic loads, the two more or less attain the same performance measures in saturated traffic load scenarios which is the case for periodic safety messages. Here we propose an 802.11-compatible repetition-based MAC protocol which fairly grants retransmission opportunities to contending neighbors. In Brief, a node each time increases the contention windows size for the subsequent transmissions of the same packet.

It has been long established that Single-hop, long range communications decreases the throughput of wireless networks due to the increased contention for media access. Multi-hop communications is a solution for dense areas, but nevertheless it would bring about unwanted delay. In reality, DSRC radios are currently able to transmit to distances as far as 300 meters. This distance is sufficient for a high speed vehicle to come to a complete stop. Hence, considering also the strict delay requirements of DSRC communications, single-hop communications would still be the best proposed for environments such as highways, etc [4]. Having said that, the quest for communication strategies in urban areas is currently limited to a diminutive number of case studies such as [9] which only consider intersections and entirely depend on the infrastructure. In [9], the authors propose a strategy to propagate event-driven safety messages along highways and through intersections. In that study, in order to reduce overhead, the furthest vehicle to the transmitter is assigned the role of packet forwarding. The furthest vehicle is the one which transmits the longest black-burst jamming signal. Although their scheme works well for emergency event-driven messages, it is not as practical for periodic message exchange due to too much jamming signal over-congesting the network. Note that in urban environments, there are situations where obstacles such as buildings block the Line-of-Sight (LOS) of close-by vehicles, forcing them to increase their transmit power to reach vehicles on the other side of the obstacle. These situations are usually when inter-vehicle communications between Non-LOS vehicles are most needed to prevent potential accidents. Acknowledging the high attenuation loss of the DSRC wave passing through the obstacle [10], the transmit power has to be extensively increased, decreasing the per-vehicle attainable throughput due to the excessive channel congestion. Note that in such environments (i.e. intersections) vehicular density is usually higher than other places, adding to the contention for channel access. Hence, it would be logical to devise multi-hop communications along with power control algorithms for such situations. Towards this goal, we incorporate a geometrical framework previously proposed by the authors in [11] into our algorithm. Here, in order to address capacity-delay tradeoffs, vehicles probabilistically decide on a single or multi-hop mode of communication upon each retransmission opportunity of a single packet. As we shall see this decision is made based on the geometrical characteristics of the neighborhood. Moreover, our method is comprehensive enough to account for any geometrical configuration of roads and obstacles and not just intersections or highways. The rest of the paper is organized as follows; In section II the geometrical definitions are provided. The actual communications scheme is elaborated in section III, followed by an example case study of an intersection in section IV. Finally the paper is concluded in section V.

II. Fundamental Geometrical Definitions

In this section we briefly introduce the essential geometrical concepts central to our analysis. A transportation geometry, named a T-Geometry, is a 3-tuple $\mathbb{T}(\Omega, L, \Gamma)$ that describes the geometry of roads on a subset of the plane. Loosely speaking, Ω represents the part of the network we are interested in; L is the set of lanes, and Γ is the set of obstacles that limit LOS. We now define these elements rigorously. $\Omega \subseteq \mathbb{R}^2$ is a *convex* and *compact* set. Further, Ω is partitioned by its *on-road* and *off-road* subsets. The on-road subset is composed of *lanes* (L) and denotes the parts of Ω a vehicle can be. The off-road subset represents all the surrounding environment of the on-road subset, and includes obstacles (Γ) and free spaces (Λ) (see Figure 1).

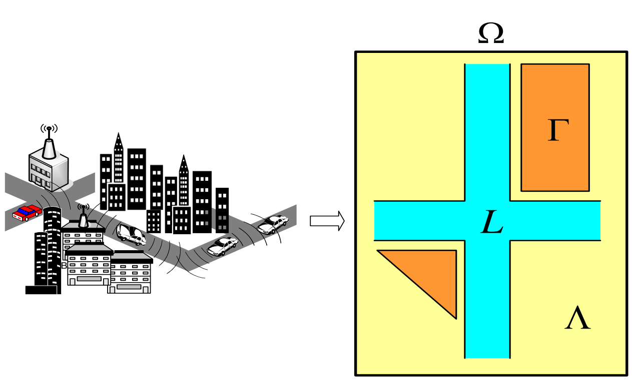

Fig. 1. The geometrical interpretation of an urban VANET.

Consider a small area in the city defined by a T-Geometry $\mathbb{T}(\Omega, L, \Gamma)$. Connectivity plays an important role in the effectiveness of the VANET in providing safety. As mentioned above, the LOS requirement is one factor that limits connectivity and obstacles are the main cause of impaired LOS. Here we provide some definitions related to connectivity and focus on worst case scenarios as they provide a good way to guarantee the performance. Note that in what follows, a pair of points in $\Omega - \Gamma$ are referred to as a LOS pair if they have LOS to each other, otherwise if an obstacle comes between them, they are called a Non-LOS (NLOS) pair.

Definition 1. *For a T-Geometry $\mathbb{T}(\Omega, L, \Gamma)$, $\kappa(\mathbb{T})$ is the maximum number of points in $\Omega - \Gamma$ such that all of the pairs consisting of these points are NLOS pairs.*

In case of vehicular networks, $\kappa(\mathbb{T})$ is the maximum number of vehicles, in an arrangement where none of them can see the other one. The value $\kappa(\mathbb{T})$ is a measure of safety of $\mathbb{T}$. Next, we show how the notion of $\kappa(\mathbb{T})$ proves useful in measuring the worst case connectivity of users in a specific geometrical configuration. This shall later prove useful in our algorithm.

Definition 2. *Consider a T-Geometry $\mathbb{T}(\Omega, L, \Gamma)$. We place n nodes in $\Omega - \Gamma$ in a way that maximizes the fraction of NLOS pairs to the total number of pairs, $\binom{n}{2}$. This maximized fraction is denoted by $\rho_n(\mathbb{T})$.*

Note that $\rho_n(\mathbb{T})$ shows, in the worst case scenario, the percentage of broken links due to obstacles. The following result is proven by the authors in [12].

Theorem 1. *Consider a T-Geometry $\mathbb{T}(\Omega, L, \Gamma)$, where n nodes are placed in $\Omega - \Gamma$. Assume $n = q\kappa(\mathbb{T}) + z$ where $q, z \in \mathbb{N}$ and $0 \leq z < \kappa(\mathbb{T})$. Then:*

$$\rho_n(\mathbb{T}) \leq 1 - \frac{q(n - \kappa(\mathbb{T}) + z)}{n(n-1)}. \tag{1}$$

with equality if the nodes are assumed to be dimensionless.

III. Communication Strategy

In this section, we address the MAC, physical and routing layers of the network by proposing appropriate channel access, power and hop control schemes. The algorithm we propose is based on retransmitting a packet in its useful lifetime. Each retransmission is carried out in a single or multi-hop fashion based on the geometry of the surroundings. Note that the useful lifetime (or acceptable delay to deliver a packet) is assumed to be the time interval between the generation of two subsequent data packets (which is 200 ms for a 5 G.Hz. GPS device). This time interval can be shared by all vehicles in a specific interference range. Note that usually the number of cars in the interference range of a specific vehicle is less than a hundred. Also the time needed to transmit a single packet is determined by the packet length and chosen data rate. If we assume a 6 Mbps data rate for vehicles operating in the 10 MHz control channel, and 250 Bytes per packet, transmission of each packet would approximately take 340 microseconds. This example is to show that even in the worst cases in terms of contention for media access (low data rate and large number of interfering cars), each vehicle can retransmit its packet several times within its useful lifetime to ensure reliable delivery and still leave enough free time slots for service data transfer.

A. Media Access Control

In this section we describe how the vehicles gain access to the channel to transmit their packets. Moreover, we introduce a scheme which fairly shares the channel between nodes and allows for the retransmission of a packet within its useful lifetime. According to the IEEE 802.11 standard, a vehicle which has a packet to transmit listens to the channel and transmits it after finding the channel idle for a DIFS amount of time. Upon transmitting its packet, other neighboring vehicles which also have a packet to send, find the channel busy and defer their transmission for a random time. This random time is $i \times t_s$, where i is a random integer uniformly selected from $\{0, \cdots, cw-1\}$ and t_s is a unit time slot duration. Here, since a vehicle performs carrier sensing prior to transmission, the major cause of packet delivery failures are the hidden nodes. After transmitting a packet, the vehicle does not have any idea about whether it has been properly received by all intended receivers (due to the lack of ACK exchange). Hence, to overcome the probable packet collisions with that of the hidden nodes', it would retransmit the packet at a later time. Moreover, having gained access to the channel, each vehicle increases its contention window size for its next retransmission opportunity. That is, a vehicle, after transmitting a copy of its packet, backs off and waits for its next turn by choosing a random integer from the interval

$$\{0, \cdots, \lfloor 2^{(i+\frac{k}{k_j})} cw \rfloor - 1\} \tag{2}$$

where i is the retransmission trial number, k is the vehicular density as observed by the vehicle and k_j is the jam density which is about 250 vehicles/mile/lane. Note how this scheme establishes fairness between the transmission opportunities of contending neighbors: a vehicle which has already had a chance to transmit its packet, would have to on average wait a longer time for its next retransmission of the same packet in comparison to a node which has not yet had a chance to transmit. Moreover, (2) accounts for the vehicular density in determining the contention window size for the subsequent retransmissions. As intuitive as it may seem, we propose a larger increase for the contention window size of vehicles in dense areas, as opposed to sparse areas. The fairness of the above MAC protocol is proven in [13].

B. Power and Hop Control Scheme

Here we account for the geometrical properties of the urban road system in order to devise an appropriate communication strategy. As stated earlier, the DSRC wave suffers excessive penetration loss when passing through obstacles such as buildings in urban areas. At the same time, increasing the transmission power unboundedly to overcome this loss would lead to over-congested channels. In these situations, we propose to utilize the $\rho_n(\mathbb{T})$ measure to decide whether to send each packet in a single or via multiple hops; hence making the scheme geometry-aware. Note that here we assume that vehicles obtain the geometrical information of their surroundings through appropriate apparatus such as GPS devices and digital maps.

Each vehicle, upon generating a packet, will deploy the channel access algorithm described in the last subsection to gain access to the channel and retransmit its packet for as many times as possible within its useful lifetime. Prior to each retransmission, a vehicle would decide whether to send this copy through single or multiple hops. There are three factors which influence this decision. First is the geometrical properties of the neighborhood. It is intuitive to propose that the higher the $\rho_n(\mathbb{T})$ it observes, the higher should be the probability of multi-hop communications. This is because $\rho_n(\mathbb{T})$ represents the maximum number of broken links (Non-LOS pairs) due to obstacles. Next is the local vehicular density. Note that in a region with low vehicular density, single hop transmission would still be a better choice to keep up with the delay requirements even if the region is highly obstructed (corresponding to high values of $\kappa(\mathbb{T})$ and $\rho_n(\mathbb{T})$). This is because there is not much contention for channel access in such sparse areas. The third factor is the time past from the generation of the packet. That is, the lower the amount of time left to the end of a packet's useful lifetime, the higher should be the probability of single-hop transmission. This is because sending a packet whose useful lifetime is nearly coming to an end via multiple hops, renders it useless even if it does reach the intended destination, but after the deadline. In sum, each vehicle would use the following transmission power, P_i, for the ith retransmission of a packet.

$$P_i = \begin{cases} P_i^1 & \textit{with probability} \quad e^{-\frac{\rho_n(\mathbb{T})k}{t_i}} \\ P_i^2 & \textit{with probability} \quad 1 - e^{-\frac{\rho_n(\mathbb{T})k}{t_i}} \end{cases} \tag{3}$$

Here, P_i^1 is the transmission power required to reach the furthest vehicle within the geocast range (distance r) of the vehicle, in a single transmission. P_i^2 is the transmission power, enough to reach the furthest vehicle within its geocast range, to which it has LOS. Note that in the latter case, the packet needs to go through additional hops (within its useful lifetime) to reach all its other intended receivers, whereas in the former case, the packet is sent in just one single-hop transmission to reach all vehicles in the geocst range. Also, t_i is the time duration from the moment of the packet's generation to its i^{th} retransmission, divided by the total useful lifetime of the packet. Finally, k is the local vehicular density, normalized by the jam density. Here we assume that each vehicle can compute its specific value for $\rho_n(\mathbb{T})$ by utilizing the on-board digital map, GPS and its long-run estimate of vehicular density.

In case we decide on a direct single hop transmission to reach the furthest vehicle in the geocast range, which happens not to be in our LOS, the penetration loss of the wave should be accounted for when calculating P_i^1. Little study has been carried out in this realm. Here we use a model developed in [14] where the authors perform logarithmic linear regressions to derive power-distance relations from their signal measurements around a block of buildings.

Having determined the power, the vehicle transmits the packet and also includes in its header, the time stamp (t_i) of the packet in case it is not going in a single hop. Note that equation (3) foresees single-hop transmission with probability 1 whenever the vehicle has LOS to all vehicles within its geocast range (i.e. when $\rho_n(\mathbb{T}) = 0$). This is consistent with the conventional paradigm of single hop transmission in such areas and renders our algorithms useful for highways as well as urban areas.

Upon receiving multi-hop packets, vehicles sort them in descending order of their time stamp in what we call the *priority stack*. The responsibility of forwarding the multi-hop packet is now incumbent on the vehicles who can see regions not in the LOS region of the original sender, but inside its geocast range. These vehicles have an additional phase in their transmission policy. First they need to determine whether they are sending their own or someone else's packet. Next they need to decide whether the packet is going in a single or via multiple hops. Upon gaining channel access, such a vehicle either transmits the packet that resides on top of its priority stack with probability t_1, where t_1 is its time stamp; or transmits its own packet with probability $1 - t_1$. This way, it transmits someone else's multi-hop packet whose lifetime is coming to an end, with a higher probability than its own packet. Note that in case of an RSE taking care of the forwarding process, this phase is not needed, since the RSE only relays other vehicle's packets. If a vehicle transmits someone else's packet, others hear this transmission and omit the corresponding packet from their own list. This happens because they are in more or less the same geographical area and hear each other's transmissions. Next time the vehicle has a turn to transmit, it chooses the next packet awaiting to be forwarded for additional hops and transmits it with the corresponding probability. If a vehicle gains enough opportunities to transmit all the packets in its priority stack, it could retransmit the ones transmitted before incase their useful lifetime has still not finished. This is why the time stamps of all the packets in the priority stack should constantly increase when they are awaiting transmission and even after they have been transmitted. A packet whose useful lifetime is over, is discarded from the priority stack. Note that when a vehicle has the responsibility of forwarding other vehicle's packets, again equation (3) is used, but this time P_i^1 and P_i^2 are adjusted so that no vehicle beyond the geocast range of the original vehicle unnecessarily receives its packets. This is possible due to location information of the vehicles being available in their status packets.

IV. Example Scenario

To make the concept more clear, we study a prototype urban area setting such as an intersection. The setting is shown in Figure 2 where two orthogonal streets meet at an intersection. We assume a fixed geocast range, r, for all the vehicles. The vehicles are assumed as points of a poisson process with an average inter-vehicle spacing of 15 meters. The mobility model includes each vehicle following its immediate leader, keeping the same distance with it all the time. The path loss model deployed for computing the transmission powers is the well-known two-ray model to reach vehicles to which we have LOS and the experimental relations developed in [14] to reach Non-LOS vehicles around buildings. Furthermore, we consider communications to be carried out in the control channel at a rate of 6 Mbps and a packet length of 250 bytes. We assume that an RSE is deployed as a means of packet relaying at the intersection. Moreover we assume that the RSE has two directional antennas, each pointing in the direction of one of the two orthogonal streets. Hence, each antenna has two narrow-band beams that are separated by 180 degrees. This way, upon receiving a multi-hop packet from a vehicle in one street, it uses the other antenna to only rebroadcast it in the other (orthogonal) street. This avoids unnecessary broadcast of the packet in the same street, preventing unwanted burden on the network.

Here, each vehicle deploys our proposed scheme to retransmit its packet for as many times within its useful lifetime. Note that as a vehicle each time doubles up the Contention Window (CW) size for its next transmission of the same packet, the RSE has a fixed CW size which is determined off-line. This is to give the RSE some precedence over vehicles to effectively perform its relaying responsibility. Upon winning access to the channel the vehicles transmit their packet in a single or multi-hop manner according to the probabilities given by equation (3). Notice that the $\rho_n(\mathbb{T})$ as seen by vehicle A is larger than the $\rho_n(\mathbb{T})$ seen by vehicle B. This is because the circle with radius r centered at vehicle A (represented with dashed (red) line) can encompass more NLOS pairs than the one centered at vehicle B (represented with dotted (blue) line). This means that for two packets who have spent an equal amount of their lifetime waiting to be transmitted for the first time at vehicles A and B, the former has a higher chance of being routed via multiple hops than the latter.

Figure 3 helps determining the optimum CW size for the RSE, for a geocast range of 250 and an inter-vehicle spacing of 15 meters. Here the optimum value (which corresponds to the highest probability of reception) happens for $CW = 16$. The reasons behind the reception probability-CW size curve having a local maxima is that, at high values of CW size, the RSE does not obtain enough opportunities to relay the multi-hop packets to their destinations; whereas for low values of CW, it redundantly rebroadcasts a packet, increasing the probability of collisions with that of the hidden nodes'.

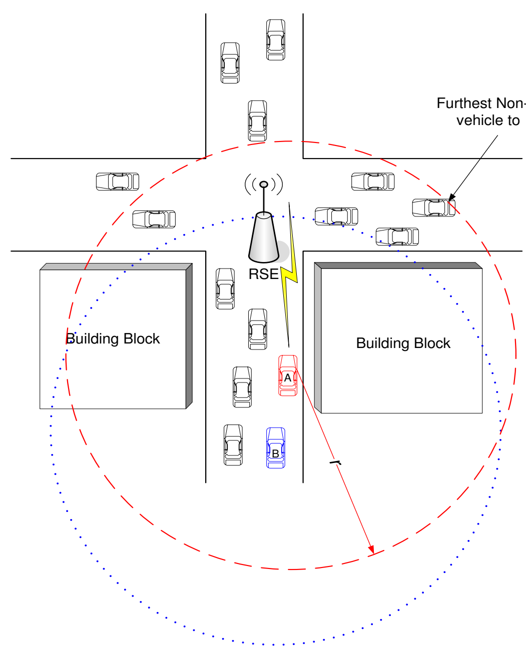

Fig. 2. Geometry-aware communications at an intersection.

Figure 4 shows the average reception probabilities of the vehicles under our proposed algorithm, compared to the scheme which deploys single hop transmission upon each of its retransmission opportunities attained via the SFR method proposed in [5]. Here, the density of the vehicles is fixed (due to the fixed inter-vehicle spacing) and the geocast range varies. As can be seen, the geometry-aware scheme outperforms the other, especially for higher geocast ranges; meaning that our scheme is especially convenient for over-congested scenarios.

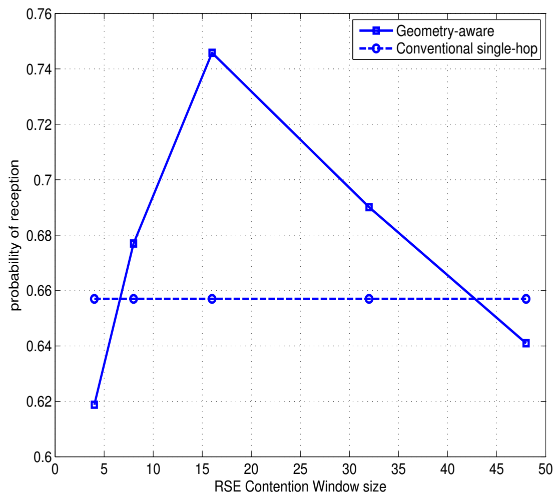

Fig. 3. The effect of Contention Window size of the RSE on the average reception probability of the proposed geometry-aware scheme. The geocast range is 250 meters.

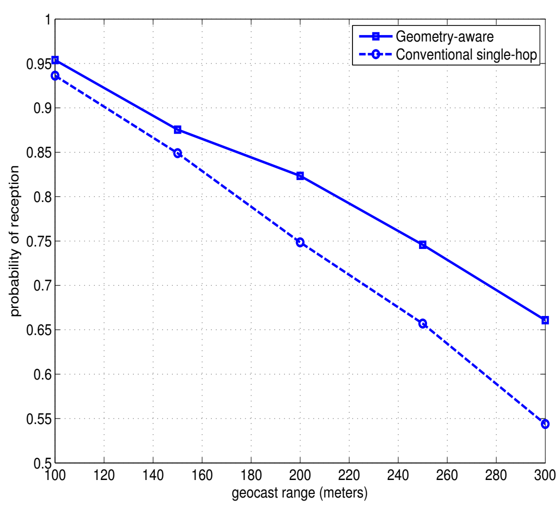

Fig. 4. Average reception probabilities for the geometry-aware scheme as opposed to the single-hop scheme. The RSE Contention Window size is optimized for each geocast range.

V. Conclusion

In this paper we proposed a comprehensive geocast scheme for the dissemination of periodic safety messages in Vehicular Ad Hoc Networks. Our objective being the development of a strategy which performs equally well in urban and rural areas, we devised a probabilistic algorithm which took the local geometrical characteristics into consideration in order to decide on a single or multi-hop mode of communications. The probabilistic architecture helped address both delay and capacity issues of the network. Moreover, the role of packet forwarding is carried out by vehicles when there is no infrastructure available. Simulation results verify the effectiveness of our algorithm regarding other geocast schemes.

References

[1] "IEEE 802.11p wireless access for vehicular environments." Draft standard, http://grouper.ieee.org/groups/802/11/.

[2] ITS, "Vehicle infrastructure integration." http://www.its.dot.gov/vii/.

[3] M. Nekoui and H. Pishro-Nik, "The effect of VII market penetration on safety and efficiency of transportation networks," in *Proceedings of the IEEE ICC Workshops 2009*, pp. 1–5, June 2009.

[4] D. Jiang, V. Taliwal, A. Meier, and W. Holfelder, "Design of 5.9 Ghz DSRC-based vehicular safety communication," *IEEE Wireless Communications*, vol. 13, October 2006.

[5] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Vehicle-to-vehicle safety messaging in DSRC," in *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, Philadelphia, U.S.A.*

[6] J. Zhu and S. Roy, "MAC for dedicated short range communications in intelligent transport system," *IEEE Communications Magazine*, vol. 41, December 2003.

[7] I. Chlamtac and A. Farago, "Making transmission schedules immune to topology changes in multi-hop packet radio networks," *IEEE/ACM Transactions on Networking*, vol. 2, December 1994.

[8] F. Farnoud and S. Valaee, "Reliable broadcast of safety messages in vehicular ad hoc netw," in *Proceedings of INFOCOM 2009*.

[9] G. Korkmaz, E. Ekici, and F. Ozguner, "Black-burst-based multihop broadcast protocols for vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 56, September 2007.

[10] G. Durgin, T. S. Rappaport, and H. Xu, "5.85-Ghz radio path loss and penetration loss measurements in and around homes and trees," *IEEE Communication Letters*, vol. 2, March 1998.

[11] M. Nekoui and H. Pishro-Nik, "A geometrical analysis of obstructed wireless networks," *to appear in the proceedings of IEEE Information Theory Workshop, 2009.*

[12] M. Nekoui and H. Pishro-Nik, "A geometrical analysis of vehicular ad-hoc networks for safety applications," in *46th Annual Allerton Conference on Communication, Control, and Computing*, pp. 1177–1183, September 2008.

[13] M. Nekoui and H. Pishro-Nik, "Reliable inter-vehicle communications for vehicular ad hoc networks," in *Proceedings of The Fourth Annual International Wireless Internet Conference (WICON 2008)*, 2008.

[14] A. Mahajan, N. Potnis, K. Gopalan, and A. Wang, "Modeling VANET deployment in urban settings," in *Proceedings of the 10th ACM Symposium on Modeling, analysis, and simulation of wireless and mobile systems.*