Geo-Opportunistic Routing for Vehicular Networks

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***Abstract*—Road topology information has been recently used to assist geographic routing in urban vehicular environments to improve the overall routing performance. However, the unreliable nature of wireless channels due to motion and obstructions still makes road topology assisted geographic routing challenging. In this article, we begin by reviewing conventional road topology assisted geographic routing protocols and investigate the robust routing protocols that address and help overcome the unreliable wireless channels. We then present TOpology-assisted Geo-Opportunistic routing (TO-GO) that incorporates topology assisted geographic routing with opportunistic forwarding. That is, the routing protocol exploits the simultaneous packet receptions induced by the broadcast nature of wireless medium and performs opportunistic forwarding via a subset of the neighbors that have received the packet correctly. Our simulation results confirm TO-GO's superior robustness to channel errors and collisions as compared to conventional topology-assisted geographic routing protocols.**

I. INTRODUCTION

The sharp increase of vehicles in the recent years has made driving more challenging and dangerous. For safe driving, leading car manufacturers have been jointly working with national government agencies to develop solutions to help drivers anticipate hazardous events and avoid traffic jams. One of the recent outcomes is a novel wireless architecture called Wireless Access for Vehicular Environment (WAVE) that provides short-range inter-vehicular communications to enable fast dissemination of emergency related messages.

While the major objective has clearly been to improve the overall safety of vehicular traffic, industry labs and academia have been exploring novel vehicular applications such as traffic management and on-board entertainment. Emerging vehicular applications often necessitate wide-area coverage using multi-hop routing protocols, which is the major departure from safety applications that require only local coverage.

However, efficient multi-hop routing in a vehicular ad hoc network (VANET) is challenging for the following reasons. First, it is a highly distributed, self-organizing network formed by moving vehicles that are characterized by very high mobility yet constrained by roads. Second, its size can scale up to hundreds of thousands of nodes. Third, nodes could suffer from severe wireless channel fading due to motion and obstructions in urban environments (e.g., building, trees, and vehicles). Finally, the vehicle density changes over time (rush hours), and the distribution of vehicles is non-uniform due to various road widths and skewed popularity of roads. Under this circumstance, most ad hoc routing protocols that discover and maintain end-to-end paths (e.g., AODV, DSR) is less preferable due to high protocol overheads. Therefore, we cannot directly use those protocols to support such emerging vehicular applications.

One of the popular routing protocols in a VANET is geographic routing where the forwarding decision by a node is primarily made based on the position of a packet's destination. A packet is greedily forwarded to a neighboring node whose distance toward the packet's destination is closer than that of the current node (called the greedy mode). If there is no such a node, i.e., a packet has reached a local maximum where it has made the maximum progress toward the destination locally, the protocol then reverts to the recovery mode. Face routing (or perimeter routing) [1], a widely used stateless recovery strategy, planarizes a network graph such that its edges intersect only at their endpoints, and then forwards a packet along one or possibly a sequence of adjacent faces (or edges), thus providing progress towards the destination node.

Geographic routing is preferable in a VANET for the following reasons. First, geographic routing is stateless; i.e., it neither exchanges link state information nor maintains established routes as in conventional mobile ad hoc routing protocols. The exchange and route maintenance are very costly in highly mobile vehicular environments. Second, it is becoming easier to support geographic routing as GPS-based navigation systems are getting cheaper and becoming a common add-on.

In urban vehicular environments, however, it is known that conventional geographic routing protocols such as Geographic Perimeter Stateless Routing (GPSR) [1] may not work well because vehicles have constrained mobility patterns due to the road structure and tend to show heterogeneous density distribution – a mixture of heavily populated and sparse road segments. In particular, the face routing could be very costly, because a packet has to travel along a sequence of adjacent faces where each step could make only small progress (as opposed to a nominal radio range) toward the destination when vehicle density is relatively high. Given that road topology is typically planar, Lochert et al. incorporated the road topology into geographic routing and proposed Geographic Perimeter Coordinator Routing (GPCR) [2] where packets can *always* be forwarded along the road segments greedily until nodes at junctions/intersections(called junction nodes). Junction nodes then decide to which road a packet must be forwarded onto based on the packet's current mode.

However, existing topology-assisted geographic routing protocols do not consider error-prone urban wireless channels due to multi-path fading and shadowing where the assumption of unit disc propagation does not hold. Geographic routing attempts to greedily forward a packet to the furthest neighboring node that is closest toward the packet's destination. The problem is that the further the distance, the higher the attenuation, and the more the likelihood of packet loss. Therefore, we want to improve the performance of topology-assisted geographic routing protocols by effectively handling unreliable wireless channels.

In this article, we first review existing geographic routing protocols such as Geographic Random Forwarding (GeRaF) [3] and Contention Based Forwarding (CBF) [4], [5] that address the unreliable channels using opportunistic forwarding where a sender takes advantage of random packet receptions in its neighboring nodes due to the error-prone wireless channel and performs opportunistic forwarding via a subset of the neighbors (called forwarding set) that have received the packet correctly. We find that these protocols often fail to exploit the full benefit of opportunistic forwarding, because they do not take the road topology into account when choosing a forwarding set. To remedy this problem, we then propose TOpology-assisted Geo-Opportunistic routing, or TO-GO, that incorporates road topology information into the forwarding set selection to better exploit the benefit of opportunistic forwarding. Unlike previous approaches [3], [4], [5], TO-GO does not relay on the unit-disk propagation assumption, but it uses the actual "intersection" of neighbors made available by 2-hop neighbor information. Simulation results confirm that TO-GO can effectively avoid poor wireless links and is thus robust to channel impairments. TO-GO can achieve up to 98% packet delivery ratio, which is 40% higher than conventional protocols in an error-prone wireless channel scenario under consideration.

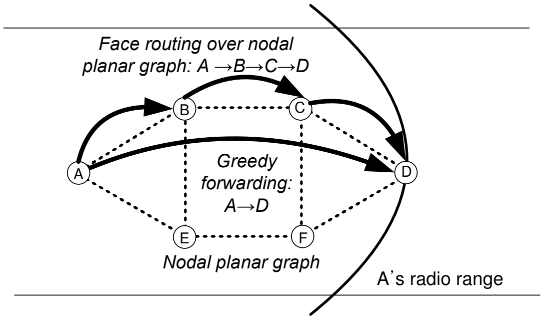


Fig. 1. Baby step problem in the recovery mode

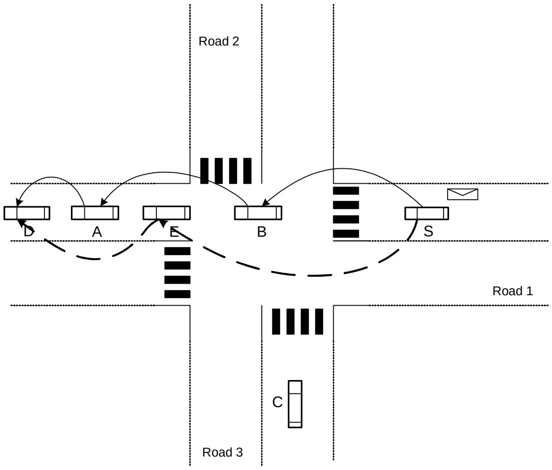


Fig. 2. Dashed arrows are GpsrJ+ and solid arrows are GPCR

II. BACKGROUNDS

In this section, we review topology-assisted geographic routing and opportunistic routing protocols, and identify limitations of existing opportunistic routing techniques when used in urban vehicular environments. Readers can find a survey of VANET routing protocols in [6].

A. Topology-Assisted Geographic Routing

Lochert *et al.* [2] found that a planarized connectivity graph for vehicles along a street could lead to a graph where a vehicle no longer sends packets to the neighboring node with the largest forward progress, which is called a "baby step" problem in the recovery mode. Recall that planarization is to transfer local connectivity graph into a planar graph by eliminating redundant edges such that its edges intersect only at their endpoints. This problem is illustrated in Figure 1 where we can greedily forward a packet along a road segment in a single hop (from A to D), but the recovery mode that uses face routing over the nodal planar graph requires three hops. For this reason, instead of relying on planarization of nodes, Lochert *et al.* [2] proposed GPCR that takes advantage of the fact that an urban map naturally forms a planar graph where a junction (or intersection) is a node, and a road segment is an edge in the graph. In GPCR, junctions are the only places where a routing decision is taken place. Packets are always greedily forwarded along the street from one junction to the other (even in the recovery mode), which solves the baby step problem. Moreover, GPSR-like face routing (using a right hand rule) is performed over the road topology graph in the recovery mode.

GpsrJ+ [7] enhances GPCR by noting that nodes do not necessarily need to stop at each junction node (see Figure 2). The key idea is that *not* every packet must be stored and forwarded by a junction node; in other words, the junction is not a necessary stop. More precisely, a packet must be stored and forwarded by a junction node only when it needs to make a left or right turn at that junction. This greatly reduces the dependency on junction nodes. In GpsrJ+, a forwarding node uses two-hop neighbor information to detect advantageous junction turns and also to better estimate a routing path. Upon learning that there are no advantageous turns, GpsrJ+ simply bypasses the junction. This two-hop prediction reduces hop counts, increases the packet delivery ratio, and obviates the need to distinguish junction nodes from ordinary nodes.

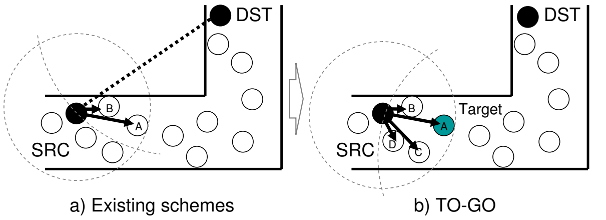
Topology-assisted geographic routing protocols can be further enhanced by checking connectivity of road segments to avoid forwarding packets along disconnected road segments [8]. Note that besides stateless geographic routings where a forwarding decision is made in each junction (e.g., GPCR and GpsrJ+), it is also possible to compute a shortest path using an urban map and then embed a set of junctions in the packet to perform source-based routing as in Geographic Source Routing (GSR) [9]. This approach may fail to provide end-to-end connectivity due to disconnected road segments, and thus, we need to proactively collect connectivity information of road segments to prune disconnected road segments as in Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE) [10]. In this article, we focus on stateless approaches such as GPCR and GpsrJ+ that do not require network wide information exchanges, and our goal is to improve their performance by taking error-prone wireless channels into account. Note that the proposed protocol in this article can also exploit the aforementioned techniques to further enhance its performance.

B. Opportunistic Routing

Geographic routing tries to greedily forward a packet to the furthest neighboring node that is closest toward the packet's destination, but the problem is that the further the distance, the higher the attenuation, and the more the likelihood of packet loss. This fact brought forth the concept of opportunistic routing [11], [12] where a sender takes advantage of random packet receptions in its neighboring nodes due to the error-prone wireless channel and of opportunistic forwarding by a subset of the neighbors that have received the packet correctly. The key challenge is to select a subset of neighbors that can make the best progress toward the destination, yet without the hidden terminal problem. When a higher priority node transmits a packet, other low priority nodes should be able to suppress forwarding to prevent redundant packet transmissions and collisions. Most opportunistic routing protocols (also called anypath routing) such as ExOR [11], Least Cost Opportunistic Routing (LCOR) [12] that do not use geographic information, require global topology and link quality information (like link state routing) to find a set of forwarding groups toward the destination; thus, they are more suitable for static wireless mesh or sensor networks.

In practice, geographic routing can also benefit from opportunistic forwarding as in Geographic Random Forwarding (GeRaF) [3], Contention Based Forwarding (CBF) [4], [5], though not optimal due to the lack of global knowledge. For forwarding set selection, researchers typically used a geometric shape faced toward the destination (e.g., triangle or lens shape [13], [4]) where nodes can hear one another. For instance, Figure 3(a) shows a lens shape forwarding set that contains node A and node B. Nodes in this forwarding region contend for packet forwarding based on a distance based timer; i.e., the further the distance from the sender, the shorter the packet expiration timer [5], [3], [13]. In the figure, node A has higher priority than node B because node A is closer to the destination. Lower priority nodes will cancel their impending transmissions when they hear a higher priority transmission.

In urban vehicular environments, however, choosing a direction toward the destination often yields a suboptimal set in terms of its size and progress because the destination may not lie on the same road segment as the current forwarding node.



a) Existing schemes

b) TO-GO

Fig. 3. The lens shape area is the forwarding region established between source and destination nodes in existing schemes, and between source and the furthest node on the current road segment (called target node) in TO-GO

For example, Figure 3 shows that the forwarding region toward the destination contains two nodes, whereas the forwarding region toward the furthest node on the current road has four nodes in the forwarding region; the latter is more robust than the former. That is exactly what TO-GO does: TO-GO focuses on a more effective forwarding set that is between the sender and the *target node* that is the furthest node on the current road segment. By incorporating the road topology information, it can better exploit opportunistic forwarding.

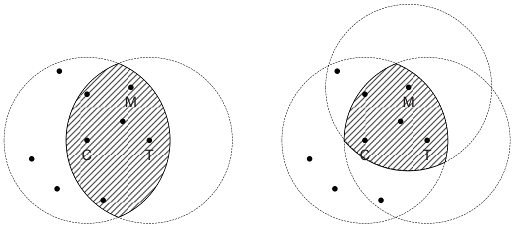
III. TO-GO DESIGN

In this section, we present the Next-hop Prediction Algorithm (NPA) that determines a packet's target node, the Forwarding Set Selection (FSS) algorithm that finds a set of candidate forwarding nodes, and the priority scheduling method that suppresses redundant packet transmissions based on a distance based timer.

A. Next-hop Prediction Algorithm

As in GpsrJ+ [7], the conventional hello beacon of a node E is augmented to include *the furthest neighbors (and their locations)* in each direction on the urban map (typically, only two neighbors except for intersection nodes). This is required to support junction forwarding prediction in both greedy and recovery modes. The beacon also contains the Bloom filter representing a set of E's neighbors, and the size of this set. Since a Bloom filter is a space efficient membership checking data structure, it enables the construction of a forwarding set while keeping the broadcast overhead at a minimum. For instance, a filter size of 150 bits (19B) can represent 15 items at a false positive rate smaller than 1%. Upon receiving a beacon, a node would have a neighbor list that contains its neighbor, every neighbor's furthest neighbors, and a Bloom filter of their neighbors and its size.

TO-GO uses this enhanced beacon to predict the target node that is either the furthest node or the *junction node*. Here, a junction node is a node that is located at the junction and can forward packets to any directions. In the greedy mode, the best forwarding node is the furthest node when its neighboring junction node's neighbor closer to the destination lies on the same road segment as the furthest node; i.e., a packet will not make left/right turns at the junction. Otherwise, the best forwarding node is the junction node. The two-hop information



a) Shaded region contains neighbors of C and T that can hear both C and T

b) Shaded region contains neighbors of C, T, and M that can hear C, T, M, and each other

Fig. 4. Forwarding set selection approximation

in enhanced beacons enables TO-GO to make an advanced decision on whether to bypass the junction node.

B. Forwarding Set Selection

After finding the target node, the current forwarding node C must determine which nodes will be in a forwarding set. In principle, the forwarding set should be selected such that nodes in the set can hear each other to prevent hidden terminal collisions. A brute force algorithm to find a forwarding set in which nodes hear one another is analogous to finding a maximal *clique* in which every node has a connection to every other node. Such a problem is NP-complete. We propose a simplified scheme to obtain an approximate forwarding set by first eliminating C's neighbors that cannot hear the target node. Out of the neighbors that remain, we then pick the neighbor that has the largest number of neighbors. Denote this neighbor as M. For each neighbor N of the current forwarding node, test its membership in M's Bloom filter. If N is in the Bloom filter and N's Bloom filter contains M, test N's membership using the Bloom filters of existing elements in the forwarding set. If N is in the Bloom filters of all these elements, add N to the set. Continue adding such N until all the neighbors of C have been checked. The algorithm takes $O(n^2)$ where n is the number of C's neighbors.

The intuition behind the approximate algorithm is that the neighbor M that has the most neighbors is in the most dense area. Despite irregular and different radio ranges, nodes selected from that region are more likely to have one another as neighbors. The forwarding set produced thus should be close to a maximal set that provides largest number of nodes as potential next hop forwarders. Note that the resulting forwarding set represented in a Bloom filter is embedded into the data packet for distributed priority scheduling.

The shaded region in Figure 4(a) contains a set of C's neighbors (denoted as $\mathbb{S}$) that can hear both current node C and target T. From the set $\mathbb{S}$, node C then picks the neighbor M that has the largest number of neighbors. In Figure 4(b), the resulting shaded region represents a subset of $\mathbb{S}$ that contains neighbors of C that can hear both M and T; and they can also hear each other.

C. Priority Scheduling

Having found the forwarding set, we want a node closer to the target node to become the next forwarder; i.e., the shorter the distance between the receiving node and the target node, the greater the progress, therefore, the shorter the timer. Unlike the timer formula in [5] where the authors assume that there is a fixed radio range R, and this range is used for normalization, we use this distance between the sending node and the *target node* for normalization, by noting the fact that radio range differs from vehicle to vehicle in reality. Hence, we set the timer T as follows:

$$T = C \times \frac{dist(\text{receiving node}, \text{target node})}{dist(\text{sending node}, \text{target node})}$$

where C is the maximum forwarding delay that varies with the transmission rate and the processing time.

IV. PERFORMANCE EVALUATION

A. Simulation Setup

The evaluation has conducted on QualNet simulator 3.95 with IEEE 802.11b DCF as the MAC with a transmission rate of 2Mbps and transmission range of 250m. We assume that nodes on different roads cannot talk to each other because of obstacles (trees, buildings, etc.). The mobility traces are generated using VanetMobiSim [14] that produces realistic urban mobility traces using macro- and micro- mobility features of the vehicular environment. Intersections are controlled by stop signs, and road segments contain speed limitations. All roads have a single lane in each direction and a speed limit of 15m/s (54 km/h). We use a grid topology in an urban area of size 1800m by 300m where the side length of a single grid is 300m.

We use a simple log-normal shadow fading model where we can vary the degree of shadow fading using a single parameter [15]: $PL(d)[dB] = PL(d_0) + 10n\log(\frac{d}{d_0}) + X_\sigma$ where n is the path loss exponent which indicates the rate at which the path loss increases with distance, d_0 is the close-in reference distance determined from measurements close to the transmitter, d is the transmitter-receiver distance, X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ to account for random and distributed log-normal shadow fading. We use $n = 2$ for the path loss exponent, and $d_0 = 0.025$ for the reference distance, which is a default setting in QualNet simulator. We vary the standard deviation σ of the zero-mean Gaussian distributed random variable X to simulate different magnitudes of shadowing effects and thereby different probabilities of packet loss.

We compare the performance of GPSR, GPCR, GpsrJ+ and TO-GO. GsprJ+ is enhanced by enabling the junction-prediction in *both* greedy and perimeter modes. The number of nodes in the network ranges from 75 to 150, with 25-node increment. We configured the constant in the timer equation as $C = 0.1$. This value maximizes throughput under channel fading conditions when the number of nodes is 150. For each node trace, we run 20 simulations and report the average value with 95% confidence interval. The duration of each run is 180 seconds. In each simulation, we select 10 random source-destination pairs for every 10 seconds where each pair transfers a stream of 1460-byte packets at a constant rate (1 packet/second).

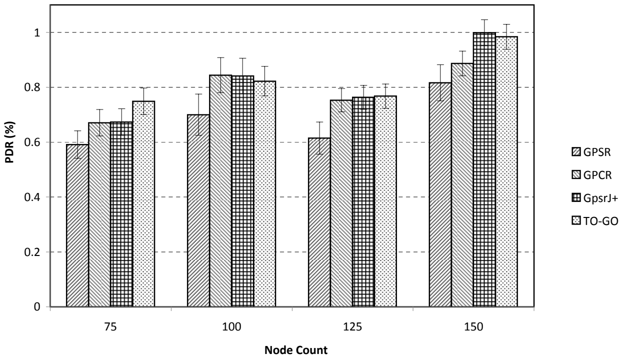


Fig. 5. PDR vs. node count

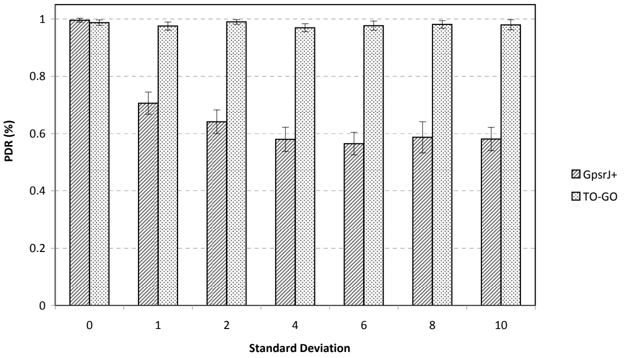


Fig. 6. PDR vs. different degrees of shadow fading (σ)

B. Simulation Results

Figure 5 shows the packet delivery rate (PDR) of GPSR, GPCR, GpsrJ+, and TO-GO with respect to node density in an error-free wireless channel. We set the σ value as zero to model 0% dropping probability. A superficial observation indicates that while GPCR, GpsrJ+, and TO-GO are almost similar to one another in PDR, GPSR always lags behind. The performance hit is due to making “baby steps” in the recovery mode; i.e., due to nodal planarization, each hop makes only a small progress toward the destination. As node density increases, the frequency of falling into the recovery mode decreases, and thus, GPSR’s PDR gradually increases to about 82%. Moreover, when there are more nodes in the network, TO-GO gains because there are more opportunities for packets to be delivered to nodes closer to the target.

We now introduce errors into the channel by varying the standard deviation σ of the Gaussian distributed random variable X ranging from 0 to 10 (in a 150-node scenario). Recall that the larger the deviation, the greater the channel error. Here, we only compare the performance of GpsrJ+ and CBF because GpsrJ+ is an enhancement of GPCR and GpsrJ+ outperforms GPCR. We plot the average PDR and latency in Figure 6 and Figure 7, respectively. When the error increases, TO-GO maintains the PDR above 96% but GpsrJ+ keeps on dropping. At $\sigma = 10$, TO-GO’s PDR remains at 98% while GpsrJ+’s PDR drops to 58%. The relatively higher latency of TO-GO from $\sigma = 1$ to $\sigma = 10$ is due to averaging these values which are not accounted for in GpsrJ+ because packets are dropped. In general, those protocols with high PDR tend to show high hop count and longer latency, because a packet has to travel more hops in order to discover a path to the destination. In TO-GO, additional delay can be incurred for retransmission due to packet collision as it always broadcasts packets; and priority scheduling in each hop also contributes to the delay.

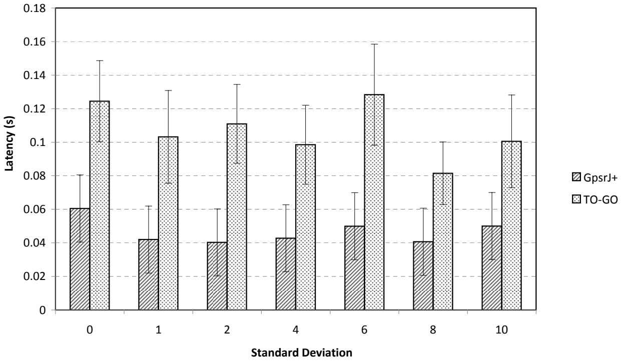


Fig. 7. Latency vs. different degrees of shadow fading (σ)

V. CONCLUSION

In this article, we reviewed road topology assisted geographic routing that uses road topology information to enhance geographic routing and illustrated that the unreliable wireless channels in urban environments make this goal challenging. For this reason, we investigated existing geographic opportunistic routing protocols that address the unreliable channels by opportunistic forwarding. We found that these protocols fail to exploit the full benefit of opportunistic forwarding, because they do not take the road topology into account when choosing a forwarding set. To overcome this limitation, we proposed TO-GO, a geographic opportunistic routing protocol that exploits road-topology information in opportunistic packet reception to improve packet delivery. As the goal in vehicular routing is to maximize the expected packet advancement to the destination, TO-GO defines a candidate forwarding set between the current sender and the target node. This set is selected using a simple junction prediction algorithm with topology information and enhanced beaconing. The forwarding set is then adjusted to reduce packet duplication and collision. We validated the robustness of TO-GO under wireless channel errors via extensive simulations.

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