Abstract—In this paper, we introduce a routing solution called “Landmark Overlays for Urban Vehicular Routing Environments” (LOUVRE), an approach that efficiently builds a landmark overlay network on top of an urban topology. We define urban junctions as overlay nodes and create an overlay link if and only if the traffic density of the underlying network guarantees the multi-hop vehicular routing between the two overlay nodes. LOUVRE contains a distributed traffic density estimation scheme which is used to evaluate the existence of an overlay link. Then, efficient routing is performed on the overlay network, guaranteeing a correct delivery of each packet. We evaluate LOUVRE against the benchmark routing protocols of GPSR and GPCR and show that LOUVRE performs higher in packet delivery and achieves lower hop count.

I. INTRODUCTION

The ever growing spread of vehicles and roadside traffic monitors with the advancement of navigation systems and the low cost of wireless network devices provide incentives for car manufacturers to equip vehicles with real-time traffic reports, promising peer-to-peer (P2P) applications, and externally-driven services to vehicles. However, for these applications and services to materialize, there is a need for standards of ubiquitous high-speed communications and homogeneous communication interfaces among different automotive manufacturers. For this purpose, the Intelligent Transportation Systems (ITS) have proposed the Wireless Access in Vehicular Environments (WAVE) standards that define an architecture that collectively enables vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) wireless communications [1].

In order to enable multi-hop wireless vehicular communications, vehicles are equipped with WAVE devices and interconnected with one other to form a Vehicular Ad-hoc Network (VANET), which is a particularly challenging class of Mobile Ad Hoc Networks (MANETs). VANETs are distributed, self-organizing networks built from moving vehicles, and are thus characterized by very high speed, a strong non-uniform distribution of vehicles, and a challenging communication environment. Such particular features often make standard networking protocols inefficient or unusable in VANETs. Indeed, protocols such as OLSR or AODV, called stateful as they maintain a routing state (routing table or routing path) in the communicating nodes, are not adapted due to the short duration of the routing states and to the scalability and overhead of their maintenance.

A direct consequence is therefore to develop stateless routing protocols, i.e., protocols that do not maintain routing states. Assuming the availability of on-board positioning devices, a promising solution is geographic routing, where routing decisions are instantaneously taken based on the geographical progress of a data packet towards the destination, also called greedy routing. There are however some topology configurations where greedy routing cannot find a node with a better progress than itself. It therefore falls into a local maximum. Such situation often happens due to topology or radio obstacles. In order to escape the local maximum, a recovery mode that relies on planarization strategies and short progress around the obstacle is triggered. So, along its path from a source to a destination, a packet often switches from a greedy phase to a recovery phase and back. Typical protocols following this scheme are the Greedy Perimeter Stateless Routing (GPSR) or the Greedy Perimeter Coordinator Routing (GPCR) [2]. We refer the reader to [3] for a complete description of geographic routing.

The major asset of geographic routing, making it a promising solution for VANETs, comes from its stateless aspect, as no routing information needs to be maintained by any node in the network [4], [5]. Geographic routing, however, is not efficient if packets spend more time in the recovery phase than in the greedy phase. Due to the lack of vehicular mobility models emphasizing this precise requirement, this limitation has been long underestimated. With the novel vehicular mobility models that recently appeared, the stateless routing approach also showed its limitations. In the challenging urban vehicular routing environment characterized by large radio obstacles and a strong non-uniform distribution of vehicles at intersections, it has notably been observed that perimeter routing was unfortunately mostly used, making geographic routing as inefficient as the protocols it was supposed to replace. Based on this observation, effort has been conducted in order to improve the greedy phase [6], [7], reduce the cost of the recovery phase [8], or both [2].

†Jerôme Harri acknowledges the support of the state of Baden-Württemberg, Tschira Foundation, PTV AG and INIT AG to the research group on Traffic Telematics.

§The availability of a GPS/Galileo receiver by each vehicle is natively assumed by both EU C2C-CC and ISO CALM.
Greedy routing however suffers from a recurrent limitation linked to its limited knowledge of local topology. Irrespective to the improvements made, it is not possible to find a best path avoiding local maxima in general topologies. A tradeoff therefore needs to be found between the robust global vision provided by stateful routing to avoid obstacles, and the scalable local vision of stateless routing for efficient data transmission. This has initially been observed and partially addressed by the Terminode Project [9], GSR [4], or GyTAR [10]. Common to all proposed solutions, landmarks are chosen to form an overlay network and to guide the greedy progress on the overlay links around obstacles. In order to select the best path on the overlay network, a route discovery procedure is either started on-demand, or greedy routing is used between the overlay nodes. To that perspective, the aforementioned approaches may be classified as geo-reactive overlay or geo-geographic overlay routing.

Similar to the ad hoc routing case, the major assets of the geo-reactive overlay routing such as GSR is the guarantee of global optimality of each path even in very challenging topologies. Its drawback is obviously its sensitivity to dynamic topology changes. However, as illustrated by Fiore and Härr [11], 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 opening overlay routes, most routes would partially use the same overlay links. Naturally then, by detaching a path from its source, a single maintenance would be required for overlapping overlay links.

With these considerations, geo proactive overlay routing becomes attractive as it guarantees a global route optimality and reduces the delay for opening overlay routes. The drawback of this approach is obviously its scalability. Yet, as it is expected to have a smaller number of landmark overlays compared to the number of vehicles, and by limiting the geo-proactive overlay routing maintenance up to a selected distance, its scalability could be guaranteed without renouncing to its efficiency.

In this paper, we therefore propose a geo-proactive overlay routing solution called “Landmark Overlays for Urban Vehicular Routing Environments” (LOUVRE), an approach that efficiently builds an overlay network on top of an urban topology and guarantees an obstacle-free geographic routing on the overlay links. The features of LOUVRE are as follows: (i) landmarks are placed at intersections\(^2\), (ii) vehicular traffic density between landmarks is distributively estimated, (iii) an overlay network between landmarks is built considering traffic density-based overlay links, (iv) the best paths from and to any landmark lying on the same grid are maintained for local routing, (v) for remote routing, packets are routed to the best neighboring grid.

In LOUVRE, a car accesses its routing table and follows the landmark paths connected by intersections to the destination. As an overlay link exists if and only if the vehicular density is sufficient for safe greedy routing to the next landmark, we significantly reduce the chances of falling into a local maximum. Moreover, we maintain the scalability of LOUVRE, first thanks to the lower number of landmarks than the number of vehicles, and second as we limit the scope of the overlay network up to a given distance.

The rest of the paper is organized as follows: Section II details the distributed density estimation used for the overlay links. Section III describes the overlay network created by LOUVRE. Section IV provides simulation results. Finally, Section V summarizes LOUVRE and provides insights on planned extensions.

II. P2P Density Discovery

Constructing the link state table of the overlay requires road density information. One way to obtain such information is by relying on road-side sensors and network infrastructures for distributing the density information. However, the drawbacks are that it requires the wide deployment of sensors and the market penetration of these sensors can take some time. We propose a P2P protocol for discovering and distributing density information.

In this protocol, each node broadcasts the IDs of its neighbors and road density information of all the roads that it has encountered. A node can approximate the density of the road it is currently on by keeping track of the number of unique neighbors it has seen on that road. In addition, it can obtain density information of other roads through these broadcast messages. When a node enters into a new road, it will flush out all the neighboring IDs of the previous road. In essence, a node computes the density information of the current road it is on and obtains density information of other roads through broadcast messages.

Nodes located at junctions do not broadcast any neighbor’s ID. They only broadcast density information of all roads. They do not keep track of the number of unique neighbors, either. When they receive IDs of its neighbors, they simply discard them. They only update their road density information from the broadcast message.

Note that it is possible that broadcast from node A on one road can reach node B on another road. A node can determine

\(^2\)Note that landmarks exist only if there are nodes at a junction. The absence of landmarks affect not only LOUVRE but also geo-geographic overlay routings since packets cannot be forwarded onto another road segment.
that this broadcast is from another road by the broadcast’s location and its NAV/GPS system and drop it. The dropping of broadcast from neighboring roads preserves the accuracy of density calculation for each road.

During times of high-traffic volume, the road density information will eventually stabilize and all nodes will have a very similar view of the road densities [12]. Once road density information stabilizes, the routing table will also stabilize and will only need to be updated when a node sees that the density information for some road has drastically changed.

A. Maintaining Scalability

Certainly, broadcasting and maintaining all road density information of all roads ever encountered is infeasible. To be more practical, we propose to only keep a fixed size list of road density information received sorted by its freshness. When the list becomes full, we replace the oldest density information with a new one, effectively throwing out the density information of a road that was encountered a long time ago. The size of the list determines the number of roads we can efficiently route to. This also places a bound on the memory and computation required to maintain link state information at each node.

B. Maintaining Freshness

Freshness of density information needs to be in both time and space. Freshness in time ensures that if density information for a road is not updated after some time, the density value for that road should be discarded. In addition, freshness in space ensures that the closer a node comes to a road, the more accurate the density information about that road becomes.

Keeping a timestamp when the density of a road is computed can be used to maintain freshness in both time and space. When a node updates the density of a road, it keeps a timestamp along with the density. Each broadcast message contains the density information of each road and the timestamp of the associated density information. When a node receives the broadcast message, it can compare its local copy of density information with the incoming density information and only update the density of the roads that have a more recent timestamp. When an update occurs, the local timestamp is replaced by the one from the message to ensure that a node only obtains the most accurate density information.

C. Reducing Overhead

In addition to defining a grid to reduce the overhead of passing density information (see Section III for detail), the overhead can be further reduced by adaptively adjusting the passing of density information. If a node consistently sees the same roads’ density information, it stops broadcasting them until the density falls below their $\text{Density}_{\text{thresh}}$ consistently. Since stable topology is most likely to occur during high-peak traffic, the overhead reduction is especially useful in reducing broadcast storm. This approach is also known in the field of congestion control under the name of transmit rate adaptation.

III. LANDMARK OVERLAYS FOR URBAN VEHICULAR ROUTING ENVIRONMENTS (LOUVRE)

We propose a geo-proactive overlay routing solution that uses density and road lengths as the metric for route creation. We discuss our assumptions and describe our routing protocol in this section.

A. Definitions and Assumptions

We define a junction as one where more than one road segment meets. A road segment is a road which cars are on and is only up to the junction. In other words, the road segment before a junction is different from the road segment after the junction. Finally, a junction node is a node at a junction.

We make the following assumptions when designing our routing protocol:

- All nodes constantly know their position and global time thanks to a NAV/GPS system, possibly enhanced with kinematic models when GPS signal is lost. Moreover, the NAV/GPS can provide the road topology information of any node given its location;
- Local time across nodes is synchronized with GPS;
- Location service allows finding the location of a node;
- Non-junction nodes on a road can only transmit to one other and not to other non-junction nodes in adjacent roads unless these non-junction nodes are on road segments that are extensions of each other. This is due to road side obstacles such as buildings and trees;
- Junction nodes, i.e. nodes located at junctions, are the only nodes that can transmit to neighboring nodes on a different road segment since they are the only types of nodes at a junction.

The key observation is that road density information does not fluctuate frequently. For busy roads, cars going out must be replenished by cars going in at about the same rate. For low-traffic roads, they do not become high-traffic roads all of a sudden. Low-traffic roads are likely to be low-traffic roads for some time. This observation true for both off-rush and rush hours [12] allows our P2P approach to obtain global stationary densities. In Section III-C, we describe how we route during bootstrapping stage where nodes only have partial road densities.

B. LOUVRE Routing

LOUVRE is an overlay link state routing protocol whose link state table contains information for routing between overlay nodes represented by junctions. We rely on the on-board NAV system to provide the map of the area. This map is used to construct a road topology graph with roads as vertices and edges between vertices denoting connectivity, i.e., there is an intersection between the two roads. When creating the overlay link state table, we only consider roads that have a density value higher than a predefined threshold and pick the route whose sum of road lengths is minimal. The minimal sum gives us the least number of hops to the destination.

We use the well-known Dijkstra’s forward search algorithm to construct the overlay link state routing table [13]. Although each table entry is a road instead of a node to preserve
scalability, the number of roads can increase when the map becomes too big. We keep the full overlay link states up to a predefined grid area. The boundary points of the grid will keep overlay link states of adjacent grids. To forward to another node $B$ outside of its grid, node $A$ would simply route to the boundary point closest to $B$ and have the boundary point route to $B$.

The density threshold is calculated using the following formula:

$$\text{Density}_{\text{thresh}} = \left\lceil \frac{L}{R \times 2} \right\rceil + 1$$

where $L$ is the length of the road and $R$ is the radio range. We multiply it by 2 to account for the fact that for a successful transmission, two nodes that are $2R$ apart must have a node in between so as to obtain full connectivity for the road. We add 1 to make sure that there is at least one car at the end of the road. The ceiling takes into account of the case where the length of the road is less than a node’s radio range. In this case, we will have two junction nodes that guarantee that packets can be forwarded onto the other roads. As long as the number of cars on the road is greater than or equal to $\text{Density}_{\text{thresh}}$, we can consider that road connected for routing. $\text{Density}_{\text{thresh}}$ calculation assumes that cars are uniformly distributed along a road. In the event where cars are not uniformly distributed, one can realize such road is disconnected if the time for the broadcast from car $A$ to reach to another car $B$ is on the order of the time it takes for $A$ to meet $B$. We automatically disqualify this road by assigning its density to 0.

We distinguish between two types of routing in LOUVRE: inter-road routing or overlay routing, and intra-road routing or underlay routing. Inter-road routing is used to route packets between roads on the overlay network, and intra-road routing is used to forward packets between cars within a road on the underlay network. Both inter-road and intra-road routing require consulting the overlay link state table to determine to which road to forward next. Inter-road routing uses this information to correctly locate a forwarding neighbor on the new road. Intra-road routing uses the next road information from the overlay network to determine the best intersection to forward packets to. Then, it would choose the neighbor that makes the furthest progress to the intersection on the underlay network.

Packets are always routed by using inter-road routing, the overlay network providing routing directions, while the underlay network providing a guaranteed greedy forwarding. Unless a node cannot find any neighbors that are on the next forwarding road, it switches to intra-road routing in order to find a neighbor closer to the intersection where it might have nodes that have neighbors on the next forwarding road. Neighbor discovery is done with periodic beacons.

Figure 1 illustrates LOUVRE’s inter- and intra-road routing from $S$ to $D$. Packets from $S$ hop greedily from one solid node to the next within each successive road until reaching $D$. When $S$ sends packets to $D'$ outside its grid, it simply routes towards nodes on Rd 6 on the boundary. These nodes maintain neighboring routing tables for cross-grid LOUVRE routing.

C. Routing during Bootstrapping Stage

There are two kinds of bootstrapping stages. The first kind is global when all nodes do not have density of any roads to start with. Packets during this phase will be routed in classical geographic routing. This kind of bootstrapping stage only appears once when the system is initially deployed. Since there will always be nodes moving on roads, density information will always be passed around in the network.

The second kind of bootstrapping stage is local when a node starts to participate in LOUVRE routing. Initially, the node will not have any knowledge of roads’ density. This bootstrapping stage lasts only in one periodical update because after one periodical update, the node will know the density of all regional roads thanks to its peers. Alternatively, a node can locally record snapshot of density information. It can consult its local copy when it first starts. The more precise the snapshot is in time, the more accurate is the density information.

D. Recovery Strategy

Despite the global vision of the overlay network, due to the lack of valid density information, it is possible, that a node is routed on a road segment and encounter a local maximum. Then, depending on the application requirements, two recovery strategies have been designed. If applications are time-sensitive (such as voice over IP), packets can be routed back to the previous road where the second best road that offers connectivity to the destination can be chosen. Packets are only dropped if an alternative road is not available. If the applications are delay-tolerant (such as FTP transfer of an archived file), packets can be stored, carried, and then forwarded until the node meets another vehicle on the next road in the routing table. We plan to study the frequency of failures and verify the need and the efficiency of the recovery strategy.

IV. EVALUATION

We evaluate our routing scheme by comparing its performance with GPSR and GPCR, two well-known geographic routing protocols that have been previously applied in VANET environments. In particular, we are interested in three types of metrics: 1) packet delivery ratio (PDR), 2) average hop count, and 3) average latency.

We implemented our routing protocol in Qualnet 3.95 using a 1000m × 1000m real city map of Washington D.C. from the TIGER database. Due to static obstacles (such as buildings), we assumed that nodes on different roads cannot communicate to one another, unless two roads share the same extension in either the horizontal or vertical direction.

The challenge in urban vehicular environments being the non-uniform distribution of vehicles with a high density of vehicles at junctions and a low density on road segments, we set the simulation environment up such that we can control the size and thus the impact of traffic jams at intersections. We therefore run simulations with 100 nodes, where 20% to 50% of them are mobile, while the others are static and located

---

3For a description of GPSR and GPCR, we refer the reader to [2].
at junctions. The traces of mobiles nodes were generated using the Intelligent Driver Model with Intersection Management (IDM-IM) by VanetMobiSim [14], an open source and freely available realistic vehicular traffic generator for network simulators. We conducted 10 simulation runs at steady-state per each mobility scenario with a random source-destination pair sending 1460-byte CBR packets every second starting from 50 seconds to 300 seconds. We took the average of all measurements and computed a 95% confidence interval.

Figure 2(a), 2(b), and 2(c) show the average PDR, hop-count, and latency with their 95% confidence interval for LOUVRE, GPSR, and GPCR. As GPSR does not consider density, it often encounters a local maximum and needs to turn to the recovery mode. This explains the low PDR and the high hop count and delay. On the other hand, since GPCR greedily routes packets along roads, it relies on the recovery phase less and thus has a reduced delay and hop-count compared to GPSR. The PDR of GPCR is also lower because GPCR detects challenging situations (loops or partitions) faster than GPSR and simply drops packets that would be hard to deliver. Due to its overlay network, LOUVRE has a global vision of the density distribution on road segments and also on local maxima, typical information that is not available to GPSR and GPCR. LOUVRE therefore improves the PDR, as it manages to deliver the packets dropped by GPCR more efficiently than GPSR. The hop count and delay are also reduced as LOUVRE does rarely encounter local maxima and therefore mostly does not use a recovery mode.

LOUVRE’s delay and hop count are higher than GPCR because LOUVRE delivers packets that are usually dropped by GPCR (illustrated by its lower PDR compared to LOUVRE’s), possibly taking detours. This observation is also consistent with the decreasing gap between GPCR and LOUVRE with an increasing ratio of mobile nodes and a better distribution of cars. Results therefore illustrated that due to the global vision of the overlay network, LOUVRE is particularly adapted for significantly non-uniformly distributed traffic (i.e., clusters at junctions and low vehicular density on road segments).

V. CONCLUSION

This paper presented LOUVRE, a density-based landmark overlay routing protocol for urban vehicular environments. We described the concept and the protocol as well as a novel distributed traffic density estimation scheme. We implemented the protocol in Qualnet and evaluated the feasibility of LOUVRE by comparing it with the benchmarks GPSR and GPCR protocols using realistic mobility traces. Results showed that due to the improved visibility of the overlay network and the routing guarantees of the underlay network, LOUVRE provides a better packet delivery ratio and hop count than the benchmark protocols. Future work includes verifying the necessity of recovery mode and comparison with GyTAR and GSR.

REFERENCES