Towards Efficient Geographic Routing in Urban Vehicular Networks

Moez Jerbi , Sidi-Mohammed Senouci , Tinku Rasheed and Yacine Ghamri-Doudane[1]

Abstract—**Vehicular ad hoc networks (VANET) have received considerable attention in recent times. Multi-hop data delivery between vehicles is an important aspect for the support of VANET-based applications. Although, data dissemination and routing have been extensively addressed, many unique characteristics of VANET together with the diversity in promising applications offer newer research challenges. This paper introduces GyTAR (improved Greedy Traffic Aware Routing protocol), an intersection-based geographical routing protocol, capable to find robust and optimal routes within urban environments. The main principle behind GyTAR is the dynamic and in-sequence selection of intersections through which data packets are forwarded to the destinations. Data forwarding between intersections in GyTAR adopts an improved greedy carry-and-forward mechanism. Evaluation of the proposed routing protocol shows significant performance improvement in comparison to other existing routing approaches. With the aid of extensive simulations, we also validate the optimality and sensitivity of significant GyTAR parameters.**

Index Terms— **geographic routing, multihop communication, traffic density, performance evaluation, vehicular communication.**

I. Introduction

WITH the advances in wireless communications technology, the concept of networked-car has received immense attention all over the world. This increasing importance has been recognized by major car manufacturers, governmental organizations, and academic community [1]. In recent years, several research initiatives including VII [2], NoW [3], CVIS [4], COMeSafety [5], C2CCC [6] among others, are being investigated, targeting to accomplish the dream of networked car and successful implementation of vehicular networks as a major step towards the realization of Intelligent Transportation Systems (ITS). As a result, an increasing number of car manufacturers are equipping vehicles with on-board computing and wireless communication devices, in-car sensors and GPS (Global Positioning System) systems, in anticipation of the deployment of large-scale vehicular networks. Along with the recent developments in VANET (Vehicular Ad-hoc Network), a number of attractive applications, unique for the vehicular setting, have emerged [7]. For example, a VANET can be used for issuing driver alerts during specific events like potential traffic jams, hazardous road conditions (slippery road warning) or accidents (to avoid multi-car collisions). Apart from road safety applications, other comfort applications include i) info-mobility (weather information, gas station or restaurants location, city leisure information, movie trailer downloads, tourist information, etc.), ii) mobile e-commerce (advertisements or announcements of sales information), iii) infotainment and interactive services (internet access, distributed games, music downloads, etc.).

In this paper, we consider a scenario where several ITS applications are deployed in a city-scale, both for car-to-car communication services and value-added infrastructure-based ITS services. To guarantee efficiency to different applications, several important issues have to be tackled, including high performance and efficient physical layer transmission schemes, fair and scalable medium access (MAC) schemes, efficient data dissemination and routing protocols, to name the most critical ones. We focus on the design of a robust routing protocol taking into account the characteristics of urban environments. To this end, we present a novel geographic routing protocol for urban VANET networks called GyTAR: *improved Greedy Traffic Aware Routing* protocol. GyTAR utilizes the vehicular traffic density and the road-topology to efficiently relay data in the network. GyTAR is well-suited for delay sensitive ad hoc applications like on-vehicle chat or gaming and equally applicable for infrastructure-related delay-tolerant applications like the access to of info-mobility or infotainment services.

The rest of the paper is structured as follows: Section II showcases several routing mechanisms proposed in the context of VANET and details the motivation of the work. Section III introduces the functioning of the protocol and details its components. Section IV describes the quantitative analysis for the key GyTAR parameters, basically to understand the optimal figure of merit for the core components of GyTAR. Section V presents the results of the performance evaluation of the proposed scheme and discusses them. Section VI concludes the paper.

II. Motivation and Related Work

Topology-based and position-based routing are two strategies of data forwarding commonly adopted for multi-hop wireless networks. The increasing availability of GPS equipped vehicles makes position-based routing a convenient routing strategy for vehicular networks as compared to topology-based approaches. However, the position-based protocols developed for MANET (Mobile Ad hoc Networks) may not be directly applied to vehicular environments owing to the unique vehicular network characteristics [9]. Several variants of position-based concept have been proposed for data forwarding

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T. R. Author is with Create-Net Research Center, Trento, Italy (e-mail: tinku.rasheed@create-net.org). Y. G. Author is with Networks and Multimedia Systems Research Group, ENSIIE, Evry, Cedex, France (e-mail: ghamri@ensiie.fr).

in vehicular networks. Three classes of forwarding strategies can be identified for position-based routing protocols: 1) restricted directional flooding, 2) hierarchical forwarding, and 3) greedy forwarding.

Many broadcast-based protocols, based on restricted directional forwarding have been proposed so far [11][12][14][15]. Among these, MDDV (*Mobility centric Data Dissemination algorithm for Vehicular networks*) [12] exploits geographic forwarding to the destination region, favoring those paths where vehicle density is higher. In MDDV, messages are carried by head vehicles, i.e., best positioned towards the destination with respect to their neighbours. UMB (Urban Multihop Protocol) [11] considers the road topology. Basically, in forwarding messages, each node selects the farthest node using location information, in order to reduce the number of hops. At each intersection, it assumes a special fixed station called repeater to deliver the message to different directions.

Unlike the broadcast-based protocols and hierarchical approaches [10], there are several works that investigate routing protocols in VANETs, adopting greedy forwarding [18][19][20][21][22]. With greedy forwarding, a node forwards a packet to a neighbour that is located closer to the destination. If this forwarding strategy fails, since there may be situations in which there is no node closer to the destination than the forwarding node, recovery strategies have to deal with it. This geographical routing approach using greedy forwarding strategy adapts well to the dynamic nature of large scale ad hoc networks. But at the same time, the direct application of such approach to VANET is not suitable. Indeed, we note that existing geographic routing like GPSR [15] are often based on a simple greedy forwarding concept (closest vehicle to the destination) without taking into account the urban environment characteristics. This leads to poor signal reception due to radio obstacles such as high-rise buildings.

Fortunately, in vehicular settings, the availability of navigation systems makes it possible to exploit maps and traffic information to guide the messages diffusion. Recent approaches examine this information to "plan" the best route to reach the destination and then use source or trajectory based routing [16] to forward messages along the desired trajectory. For example, GVGrid [18] is a QoS-based VANET routing protocol which exploits geographical information. It divides a geographical area into grids and forwards packets along the roads crossing different grids. However, it assumes a dense network, which does not always hold true in VANETs. The work in [19] computes the sequence of intersections that must be traversed by each packet to reach its destination; this information is then included in the packet in the form of geographic source routing. A-STAR (*Anchor-based Street and Traffic Aware Routing*) [20] is also an intersection-based routing scheme designed specifically for IVC in a city environment. It features the novel use of city bus route information to identify anchor paths of higher connectivity so that more packets can be delivered to their destinations successfully. Another recent example of vehicular routing that exploits the availability of map information is discussed in [21]. This routing protocol, aimed at sparsely connected vehicular networks, uses a store and forward technique and approaches the destination by selecting the direction with the lowest estimated delay to the destination. The forwarding algorithm selects the next hop by choosing either the neighbour that is nearest to the destination (which may lead to routing loops), or a neighbour that is approaching the target location.

Most of these protocols do not take into account the vehicular traffic, which means that such algorithms may fail in case they try to forward a packet along streets where no vehicles are moving. Such streets should be considered as 'broken links' in the topology. Moreover, a packet can be received by a node that has no neighbours nearer to the receiver than the node itself. In this case, the problem of a packet having reached a local maximum arises. These problems can be overcome to some extent knowing the real topology, by opting to use only streets where vehicular traffic exists. In addition, in [19] and [20], forwarding a packet between two successive intersections is done on the basis of a simple greedy forwarding mechanism. This classic greedy approach works well since it is independent of topological changes but it suffers from inaccurate neighbour tables since it does not consider the vehicle direction and velocity. Thus, it may be possible to lose some good candidate nodes to forward the packets.

To provide a solution to the above-mentioned problems, we propose a new intersection-based geographical routing protocol capable to find robust routes within city environments. The proposed protocol is conceived to relay data in the vehicular network for distributed infotainment applications and user services which require multi-hop communication, such as web browsing, chat, file sharing, games, delivering advertisements and announcements about sale information, the available parking lot at a parking place etc. In other words, this routing protocol ensures the user connectivity in specific environments, allows service continuity and possible extension to the wired network. In the following section, we give a detailed description of our approach and present its added value compared to other existing vehicular routing protocols.

III. GyTAR: improved Greedy Traffic Aware Routing Protocol

A. Hypothesis

GyTAR considers that each vehicle in the network knows its own position and speed using GPS and can determine the position of their neighbouring intersections through pre-loaded digital maps, which provides a street-level map. The presence of such kind of maps is a valid assumption since vehicles are becoming increasingly equipped with on-board navigation systems. Furthermore, a sending node needs to know the current geographical position of the destination in order to make a routing decision. This is achieved, in real time, thanks to the location service, which can be made available, for example, using city-scale Wireless Sensor Networks (WSN) [17]. Finally, we assume that each vehicle is required to maintain a neighbour table where the position, velocity and direction of each neighbouring vehicle are recorded. This table is built and updated thanks to the periodic exchange of *Hello* packets by all vehicles.

B. GyTAR Overview

GyTAR is an intersection-based geographical routing protocol, capable to find robust routes, designed to work optimally within urban environments. To reach this objective, the GyTAR scheme is organised into three mechanisms: (i) a completely decentralized scheme for the estimation of the vehicular traffic density in city-roads (ii) a mechanism for the dynamic selection of the intersections through which packets are forwarded to reach their destination, and (iii) an improved greedy forwarding mechanism between two intersections. Using GyTAR, packets will move successively closer towards the destination along the streets where there are enough vehicles providing connectivity. We do not impose any restriction to the communication model, and GyTAR is applicable to both completely ad hoc (mobile sources and destinations, e.g., gaming on-the-move applications) and infrastructure-based routing (fixed destination, e.g., a service hotspot).

1) Traffic Density Estimation

GyTAR includes a completely decentralized mechanism for the estimation of vehicular traffic density in city-roads. The decentralized approach is based on the traffic information exchanged, updated and maintained among vehicles in the roads and revolves around the core idea of information relaying between groups of vehicles rather than individual vehicles. More precisely, the vehicles are arranged into location-based groups. For that, each road (section of street between two intersections) is dissected into small fixed area cells, each defining a group. Note that the cell size depends on the transmission range of vehicles (around 250 m) and the coordinates of the cell center gives the cell a unique identifier (ID). Cells, and hence groups, overlap in such a way that any vehicle moving from one cell to the next belongs at least to one group. Among vehicles within the zone leader[2], the closest vehicle to the cell center is considered as the group leader for a given duration. Note that the overlapping zone is so small that it is not possible that a vehicle is considered to be group leader of both adjacent cells.

Cells Data Packet (CDP)		
Road ID	Time	
Cell ID	Cell 's Center (Position)	Cell's Density

Figure 1. CDP message format.

Local density information is then computed by each group leader and relayed between groups using Cell Density Packet (CDP). The CDP gathers the density[3] of a given road (i.e., all its cells). As illustrated in Figure 1, each CDP also contains fields identifying the road ID, transmission time[4], and the list of route anchors (position of cells centre).

The CDP is generated by vehicles which have already been group leaders once they reach a road intersection. This has two benefits. First, it limits the generation of CDP messages, avoiding scalability and overhead issues. Second, it is adapted to the dynamics of the vehicular traffic within the road segment. Indeed, when the vehicular traffic decreases, the traffic density changes fast. In this case, speed of group leader vehicles increases, which in turn increases the frequency of CDP packets. Conversely, as the vehicular traffic increases, the traffic density changes slowly. In this case, speed of group leader vehicles decreases, which in turn decreases the frequency of CDP packets.

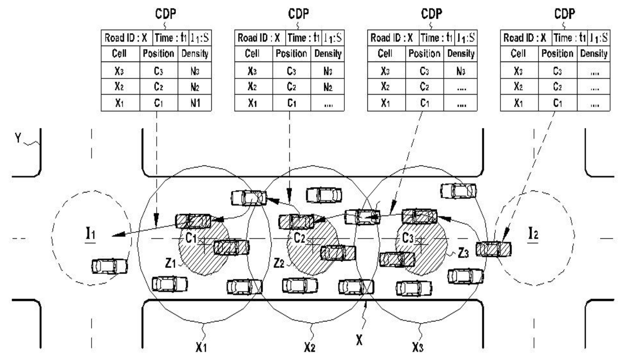


Figure 2. Relaying local density information between groups.

When initiating the CDP, a vehicle records the road ID, the transmission time[4] and a list of anchors through which the packet has to pass while traveling to the other intersection, and then, sends the packet in the backward direction (see Figure 2). The CDP header includes a limited list of anchors corresponding to the position of the cells' centers. Then, the CDP is forwarded towards the first anchor on the basis of our improved greedy strategy (described in the subsection 3.2.3). Once the message is received by a group leader (the closest vehicle to the cell center), this later updates it by including the density of the corresponding cell (the number of its neighbours which belong to the corresponding road[5]) and then forwards it towards the next anchor. This is repeated until the CDP is completed while arriving to the destination intersection. This is illustrated in Figure 2 where the CDP packet is generated by the vehicle leaving road X. Such packet is updated by vehicles around cells' centers (C_1, C_2, and C_3) as it is traveling from one cell to another.

After the last anchor (the destination intersection) is reached, the CDP is propagated to vehicles which are around the intersection so that all vehicles traversing through the intersection will receive it. These vehicles analyze the packet content and calculate the density for the respective road from which the CDP was received. This analysis is done by computing (i) the average number of vehicles per cell (Navg = $\frac{1}{Nc} x \sum_{i=1}^{Nc} Ni$ where Nc is the total number of cells within the road) and (ii) the standard deviation of cells densities ($\sigma = \sqrt{\left(\frac{1}{Nc} x \left(\sum_{i=1}^{Nc} (Ni - Navg)^2\right)\right)}$).

Note that the standard deviation indicates how much variation there is away from the N_{avg}: a large standard deviation indicates that the cells densities are far from the mean and a small standard deviation indicates that they are clustered

[2] A small area around a cell center where a vehicle is elected as a group leader (the hatched area in Fig.2).

[3] By density, we mean the number of vehicles within the cell.

[4] Note that all the vehicles are synchronized by GPS.

[5] This information is already available in the neighbors table of the elected group leader.

closely around the mean. The density estimation mechanism has several standalone applications, apart from being a core component of the routing protocol. These are explained more in detail in [13].

2) *Intersection Selection*

Similar to position-based source routing, GyTAR adopts an anchor-based routing approach with street awareness. Thus, data packets are routed between vehicles, following the street map topology. However, unlike GSR and A-STAR, where the sending node statically computes a sequence of intersections the packet has to traverse in order to reach the destination, intermediate intersections in GyTAR are chosen dynamically and in sequence, considering both the variation in the vehicular traffic and distance to destination. Partial successive computation of the path has a threefold advantage: (i) the size of packet header is fixed; (ii) the computation of subsequent anchors is done exploiting more updated information about vehicular traffic distribution; (iii) subsequent anchors can be computed exploiting updated information about the current position of the destination.

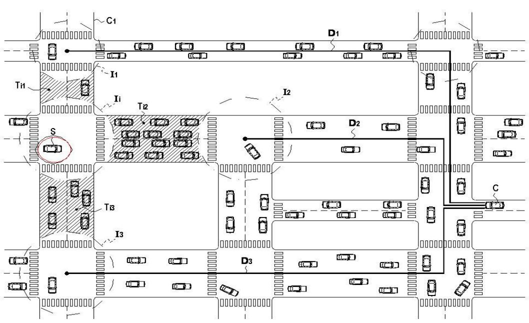


Figure 3. Selecting intersections in GyTAR.

When selecting the next destination intersection, a node (the sending vehicle or an intermediate vehicle in an intersection) looks for the position of the neighbouring intersections using the map. A score is attributed to each intersection considering the traffic density and the curvemetric distance[6] to the destination. The best destination intersection (i.e., the intersection with the highest score) is the geographically closest intersection to the destination vehicle having the highest vehicular traffic.

Figure 3 shows an example of how the next intersection is selected. In this scenario, once vehicle S (located in the intersection **Ii**) receives a packet, it computes the score of each neighbouring intersection. Considering its curvemetric distance to the destination (D2) and the traffic density (Ti2), intersection (I2) will have the highest score. It is then chosen as the next anchor.

Using this real time traffic aware approach, the determined route will be the one with higher connectivity.

To formally estimate the score of an intersection, we define the following notations:

- J: the next candidate intersection;
- I: the current intersection;
- D_j: the curvemetric distance from the candidate intersection J to the destination;
- D_i: the curvemetric distance from the current intersection to the destination;
- $D_p = D_j/D_i$ (D_p determines the closeness of the candidate intersection to the destination point);
- Between intersection I and intersection J:
  - N_i : number of vehicles within cell i;
  - N_{con}: constant which represents the ideal connectivity degree we can have within a cell;
  - N_c : number of cells[7] between I and J;
  - N_{avg}: average number of vehicles per cell ($N_{avg} = \frac{1}{Nc} x \sum_{i=1}^{Nc} Ni$) (1);
  - σ : standard deviation of cells density N_i (it indicates how much variation there is away from the N_{avg}); $\sigma = \sqrt{\left(\frac{1}{Nc} x \left(\sum_{i=1}^{Nc} (Ni - Navg)^2\right)\right)}$ (2);
- α, β: used as weighting factors for the distance and vehicular traffic respectively (with $\alpha + \beta = 1$).

Hence,

$$Score(J) = \alpha \cdot f(Dj) + \beta \cdot g(Tj) = \alpha \times [1 - D_p] + \beta \times \left[\min\left(\frac{1}{\sigma+1} * \frac{N_{avg}}{N_{con}}\right), 1\right] \quad (3)$$

As we can see, this equation is based on two factors:

- The first factor Dj is a measure of the distance to the destination in road length. Shorter distances to the destination are preferred. To calculate the score distance, we proposed the following function: f (Dj) = $[1 - D_p]$ where D_p determines the closeness of the candidate intersection to the destination point. Hence, the closer the potential intersection j is, the lower the parameter D_p is and the higher the score distance is.

Note that when the candidate intersection corresponds to the final destination intersection, D_p is equal to zero, which corresponds to the highest score distance we could have (f(Dj)=1).

- The second factor Tj is a measure of the traffic density between the current intersection and the potential intersection j. Well balanced streets with higher density are preferred. One possible function to calculate the score density is,

$$g(Tj) = \left[\min\left(\frac{1}{\sigma+1} * \frac{N_{avg}}{N_{con}}\right), 1\right]$$

As we can see, the score density depends on three parameters (N_{avg}, σ and N_{con}). Indeed, for a given street, the traffic density estimation module of GyTAR provides the density Ni of each cell. The cells density is then used to calculate N_{avg} (average number of vehicles per cell) using equation (1) and σ (standard deviation of cells density) using equation (2).

[6] This term describes the distance measured when following the geometric shape of a road.

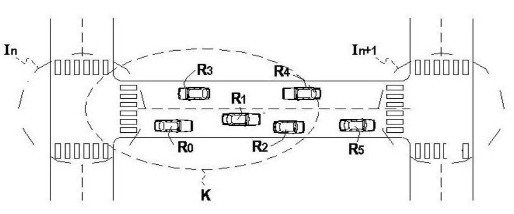
[7] The cell size is determined based on the wireless transmission range of vehicles.

Whereas N_{con} is a constant (set to twelve[8]) which represents the ideal connectivity degree we can have within a cell to ensure a good end-to-end connectivity. Thus, $\frac{N_{avg}}{N_{con}}$ determines how high the whole street density is, while σ indicates if the street is well balanced or not. Hence, by multiplying $\left(N_{avg} / N_{con} \right)$ with $1/(\sigma+1)$, we penalize streets with a large standard deviation since this corresponds to scenarios where we have gaps within the street (isolated clusters of vehicles). Note that like f(Dj), g(Tj) should provide values less than 1. This is why we used the min function.

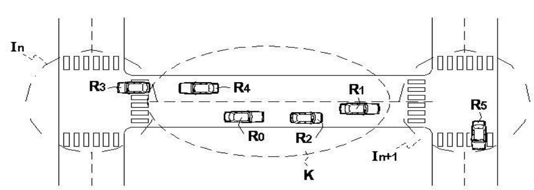
3) Forwarding data between two intersections

After determining the destination intersection, the improved greedy strategy is used to forward packets towards the intersection (from the source intersection). For that, all data packets are marked by the location of the next intersection. Each vehicle maintains a neighbour table in which the velocity vector information of each neighbour vehicle is recorded. This table is updated through *Hello* messages exchanged periodically by all vehicles. Thus, when a data packet is received, the forwarding vehicle predicts the position of each neighbour using the corresponding recorded information (velocity, direction and the latest known position), and then selects the next hop neighbour (the closest to the destination intersection). Note that in the case where there are two closest vehicles to the destination intersection, the forwarding vehicle picks up one randomly.

This approach is illustrated in Figure 4, where vehicle (R1), which is moving in the same direction as the forwarding vehicle with a speed greater than vehicle (R2), will be chosen as next hop since at current time (t_2), it is the closest to the next intersection (see figure (4a)). However, without using prediction, the forwarding vehicle would choose vehicle (R4) as the next hop instead of vehicle (R1) since it was the closest to the destination intersection at time ($t_1 < t_2$) (last time the neighbour table was updated (see figure (4b)). Note that most of the existing greedy-based routing protocols do not use the prediction and consequently, they might lose some good candidates to forward data packets.



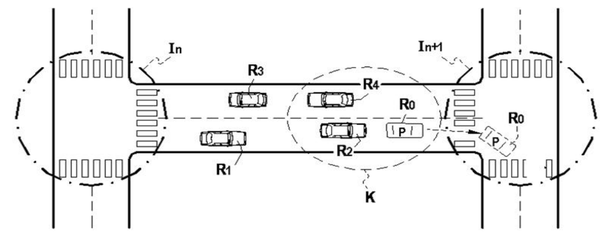
(a) Configuration at $t_1 < t_2$



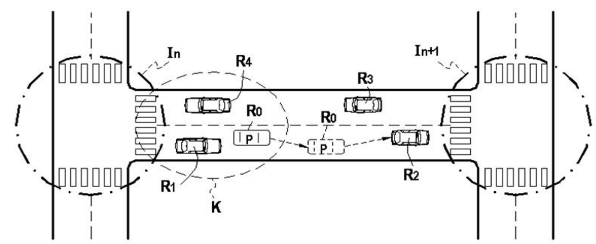
(b) Configuration at current time t_2

Figure 4: Forwarding data between 2 intersections with improved greedy strategy.

Recovery Strategy: Despite the improved greedy routing strategy, the risk remains that a packet gets stuck in a local optimum (the forwarding vehicle might be the closest to the next intersection). Hence, a recovery strategy is required. The recovery strategy adopted by GyTAR is based on the idea of 'carry- and-forward' [23]: the forwarding vehicle of the packet in a recovery mode will carry the packet until the next intersection (see Figure 5 (a)) or until another vehicle, closer to the destination intersection, enters/reaches its transmission range (see Figure 5 (b)).



(a) Forwarding vehicle (R0) carrying data packet to the next intersection.



(b) Forwarding vehicle carrying data packet to the first vehicle reaching its radio range.

Figure 5. Recovery strategy used in a local optimum.

IV. Fine Tuning GyTAR parameters

A. Ideal connectivity degree N_{con}

From equation (3), the score of an intersection J is the sum of the distance score and the density score. To compute the density score, the section of street between the intersections I and J is divided into N_c cells as shown in Figure 2. The constant (N_{con}) represents the ideal connectivity degree we can have within a cell. Next, we assume that the distribution of the distance between vehicles follows the exponential distribution. Usually, when vehicles drive freely, the distribution of the time headway is the exponential distribution [24]. When the speeds of the vehicles in the traffic flow are supposed to be uniform, the distribution of the space headway will have the same distribution of the time headway. Thus, the distribution of the distance *d* between vehicles is expressed by the exponential distribution:

$$f(d) = \lambda \exp(-\lambda . d), \qquad (4)$$

where λ represents the traffic density in [vehicles/km].

Let R be the radio communication range. The probability F(R, λ) that a vehicle exists within the communication range R is expressed as:

[8] The choice of this value is studied in section 4.1.

$$F(R,\lambda) = P(d < R) = \int_0^R f(d) = 1 - \exp(-\lambda . R) \cdot \quad (5)$$

Let ρ denote the average number of vehicles per cell. Since the radius of a cell is equal to the radio range R and the communication radio range is set to 0.250 Km, ρ represents the traffic density in [vehicles/0.5 km]. Hence, the parameter λ of the exponential distribution of the distance *d* can be expressed as function of the parameter ρ (λ = 2.ρ). Consequently, the probability F(R, ρ) that a vehicle exists within the communication range R is expressed as:

$$F(R,\rho) = 1 - \exp(-2.\rho.R) \quad (6)$$

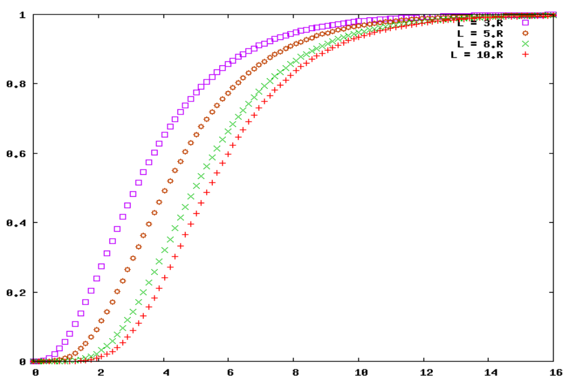


Figure 6. Continuous connectivity over cell density.

Consider *m* vehicles on a single-lane road of length L. The *m* cars determine *m* − 1 inter-vehicle segments. The probability that there is continuous radio connectivity between vehicles along the road is equal to the probability that there are *m* consecutive vehicles driving at distances of less than R, which can be calculated as:

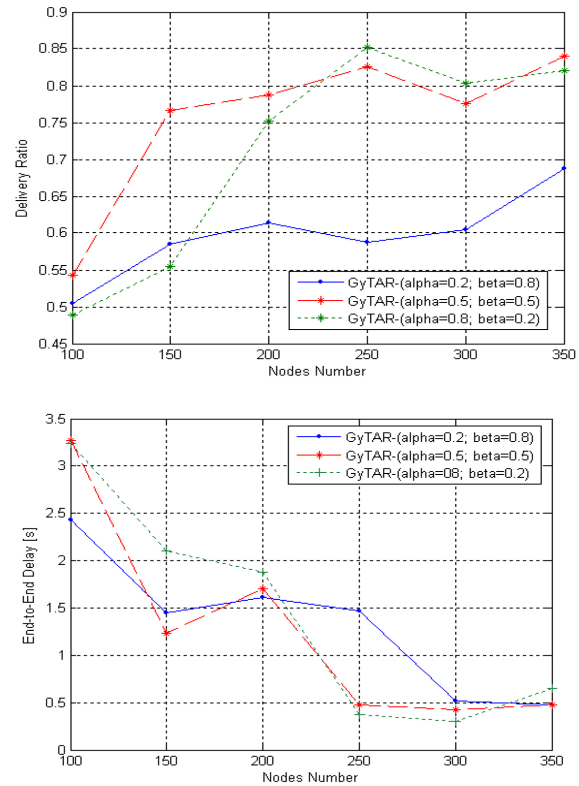
$$P(\rho, R, m) = \prod_{1}^{m-1} F(R,\rho) = [1 - \exp(-2.\rho.R)]^m \quad (7)$$

where *m* could be approximated by the integer value of [L/R].

Figure 6 presents the probability of continuous radio connectivity as a function of ρ (the average number of vehicles per cell) for different road lengths. The radio range is set to 250 m. As seen in the figure, when the density ρ increases, the probability of connectivity improves noticeably.

B. *Sensitivity of the key parameters Alpha and Beta*

In this subsection, we analyze the sensitivity of the key parameters of the intersection selection algorithm in order to determine the good balance between distance and density. We simulated the performance of GyTAR for different values of α and β. All the key parameters of the simulation are summarized in table III of the following section. We measured the achieved packet delivery rate (Figure 7 (a)) and end-to-end delay (Figure 7 (b)) versus the vehicle density (number of vehicles). Each point in the graphs is based on 10 independent simulation runs.



Data transmission rate = 0.2 [s] (5 packets / second)
Figure 7. (a) Delivery ratio and (b) End-to-end delay vs. nodes number.

The analysis shows that, in most of the cases, more packets are delivered with lower delay as the number of vehicles increases. This is expected since the probability of connectivity is increased with the increasing number of vehicles.

GyTAR variant that favors distance [(α,β) = (0.8, 0.2)] achieves higher delivery ratio when there is high vehicle density (number of vehicles between 200 and 300), whereas GyTAR variant that favors density [(α,β) = (0.2, 0.8)], show better results in terms of delivery ratio and delay for low vehicle density (number of vehicles between 100 and 200). This is mainly because for high vehicle density (which means most of streets are with high connectivity), it is better to favor distance in order to find the closest anchors (geographically) to destination, which reduces delivery delay. However, if there are not enough vehicles on streets to provide connectivity between intersections, favoring density while selecting anchors reduces the number of packets dropped due to the local maximum. Figure 7 shows also that GyTAR with the value of (α,β) set to (0.5; 0.5) achieves the highest packet delivery ratio and a low end-to-end delay for almost different nodes density.

From this evaluation, we found that the performance of GyTAR is sensitive to the values of (α,β) and its best results are obtained when these values are set to (0.5; 0.5)[9].

V. Performance Evaluation

In this section, we evaluate the performance of GyTAR. We carried out the evaluation using the Qualnet simulator. We first analyze the density estimation mechanism independently to

[9] Note that these values will be considered while evaluating the performance of GyTAR.

show its accuracy. Then, we realize a deep performance analysis of GyTAR.

Table II. Simulation setup for distributed density estimation.

SIMULATION / SCENARIO	
Simulation Time	400 s
Road length	2500 m
Mobility Model	VanetMobisim [25]
Average vehicle velocity (city)	30 km/h (slow vehicles) 50 km/h (normal vehicles)
Number of vehicles	60-120

MAC / ROUTING	
MAC protocol	802.11 DCF
Pause Time	3 à 6 s
Trans. Range	~266 m
Propagation model	Two ray ground reflection
Zone Leader[1] Radius	40 m

A. Analysis of the distributed density estimation

We simulated a 2500 m long, straight road, with two bi-directional lanes (Figure 8). This section of road is dissected into five overlapping cells. We introduce a traffic light as a perturbation source diametrically along the middle-cell. Substantially, the effect is to create stop-and-go waves in the traffic stream. All the key parameters of the simulation are summarized in Table II.

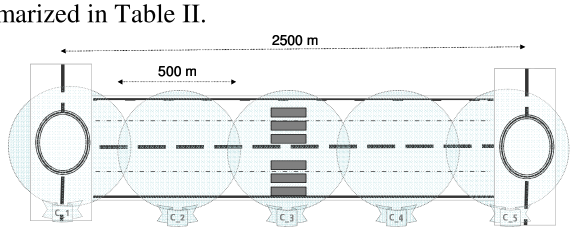


Figure 8. Simulation scenario.

Simulation Results and Analysis

The results shown in the following figures have been obtained on the 2500 m road shown in Figure 8. The number of vehicles (N_{total}) is set to 60 (Low Density, LD) and 120 (High Density, HD). Figures 9, 10 and 11 report the estimated and the real densities over time in the first, second and fourth cell respectively. Note that the real values are computed from the trace files generated by VanetMobisim [26], while the estimated values correspond to values reported in the density field of the CDP packets.

Figure 9 shows the average number of vehicles (both real [N_{real}] and estimated [$N_{estimated}$]) within cell 1, which is the first one in our road segment scenario. The relative error, defined as $|N_{estimated} - N_{real}| / N_{total}$, is observed to be between 0 and 3% for the low density scenario and between 0 and 4% for the dense network, which are very low. This is explained mostly by the fact that the cell density is estimated by a group leader, a vehicle located very close to the cell center and able to hear hello messages of its neighbouring vehicles within the cell.

Figure 10 depicts the average time it takes for a CDP packet to traverse the road segment. It is observed that the delivery delay in the sparse network is higher than in the dense network. This is because at higher density, the problem of local optimum (the forwarding vehicle might be the closest to the next anchor) is encountered rarely.

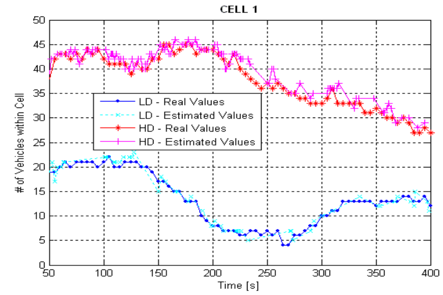


Figure 9. Number of vehicles within cell 1 over time (for low and high density scenarios).

Also, it is observed that longer delays might cause more errors while estimating the number of vehicles within some cells. For example, the highest delay in the scenario with high density happens at t = 170 s. At the same time, we note an error of 5% between the estimated values and the real values within cell 4. This is confirmed in the low density scenario as well, where the highest error in cell 4 (8.3%) happened at t = 367 s, instant for which we have a high delivery delay (7 s). This is because a long delay implies that some density information taken in the front of the road had changed leading to the computed errors. Note that such situations are rare and thus, the errors remain small and punctual. In general, simulation results show a good level of accuracy and promptness for both low and high density scenarios.

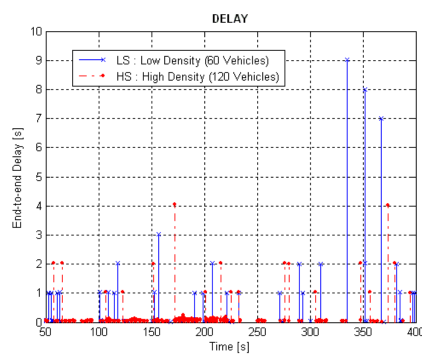


Figure 10. End-to-end delay over time (for low and high density scenarios).

B. Analysis of GyTAR

Table III. Simulation setup.

In order to evaluate GyTAR performance, a more complex simulation setting is used. This one is described in the two subsections below. Our simulation study compares four protocols. Two versions of GyTAR that we implemented: B-GyTAR (Basic GyTAR without local recovery, i.e., a packet is simply dropped when it encounters a local optimum situation), and GyTAR with local recovery. A version of the position-based vehicular routing protocol GSR (which more closely resembles the nature of our algorithm) that we also implemented since there is not any publicly available implementation of the protocol and the geographic routing protocol LAR [25].

1) Mobility Model

The mobility model used in the simulation has a great impact on the studied protocols behavior and the obtained simulation results [26]. Hence, cars are initially distributed over the road and start moving on both directions with an average speed of 30 or 50 km/h depending on vehicle type (slow or normal vehicle) and considering both macro-mobility (road topology, street characterization, car class dependent constraints, traffic signs, etc.) and micro-mobility (car-to-car interactions, car-to-road interactions, acceleration and deceleration, overtaking, etc.).

SIMULATION / SCENARIO	
Simulation Time	250 s
Map Size	2500 x 2000 m^2
Mobility Model	VanetMobisim [25]
Number of intersections	9
Number of roads	23
Number of vehicles	100-350
Average vehicles velocity (city)	30 km/h (slow vehicles) 50 km/h (normal vehicles)
MAC / ROUTING	
MAC protocol	802.11 DCF
Channel Capacity	2 Mbps
Trans. Range	~266 m
Traffic Model	15 CBR connections
Packet sending rate	0.1 – 1 second
Weighting factors (α; β)	(0.5;0.5)
GyTAR hello interval	1 second
Data packet size	512 bytes

2) Simulation Setup

The vehicular movement pattern generation is based on a 2500 × 2000 m² rectangle street area, which consists of 9 intersections and 23 two way roads. In each road, a certain number of vehicles are deployed randomly. For the displacement behavior, each vehicle chooses one of the intersections as its destination, and moves along the road to this destination with an average speed ranging from 30 to 50 km/h.

The number of vehicles is varied from 100 to 350. The simulation results are averaged over 10 runs. 15 random connections were established using CBR traffic at 0.1-1 second (1-10 packet(s)/second) with a packet size of 512 bytes. The weighting factors (α; β) are set to (0.5;0.5). All the key parameters of our simulation are summarized in Table III.

3) Simulation Results and Analysis

The performance metrics used to evaluate the simulation results are:

- *packet delivery ratio*: the fraction of originated data packets that are successfully delivered to their destination vehicles;
- *end-to-end delay*: the average time it takes for a packet to traverse the network from its source to destination; and
- *routing overhead*: the ratio between the total number of bytes of control packets and the cumulative size of data packets delivered to the destinations and control packets.

The routing protocols are compared under various data transmission rates and various vehicle densities. The detailed analysis of the simulation results is given in the following:

Packet Delivery Ratio: Figure 11a shows that GyTAR achieves the highest packet delivery ratio for almost all packet sending rates. This is mainly because in GyTAR, the path is determined progressively following road traffic density and urban environment characteristics. Hence, a packet will move successively closer towards the destination along streets where there are enough vehicles to provide connectivity. Whereas in GSR, a complete sequence of waypoints is computed before the packet is originally transmitted by the source and without considering the vehicular traffic. Consequently, some data packets can not reach their destination due to a lack of connectivity on some sections of streets.

LAR achieves a lower delivery ratio than GyTAR because it uses a route discovery mechanism. Consequently, some data packets can not reach their destination as it is very difficult to maintain an end-to-end connection in the vehicular environment (frequent topology change and network fragmentation).

In general, GyTAR has a much higher delivery ratio than B-GyTAR (up to 20% relative improvement). This is because with local recovery, packets that encounter local optimum can be rerouted and delivered instead of being dropped. The increase in packets delivery ratio is more significant at lower node number where local optimum is encountered frequently. For example, with local recovery, GyTAR delivers 20% more packets than B-GyTAR at 200 nodes, while only 7% more at 300 nodes.

End-to-End Delay: As shown in Figure 11b, GyTAR and B-GyTAR achieve a much lower end–to-end delay than LAR and GSR in all configurations. This is because in GyTAR, the number of hops involved to deliver packets is reduced due to the improved greedy strategy used to forward packets between intersections, and also because GyTAR does not need to keep track of an end-to-end route before sending data packets: the route is discovered progressively when relaying data packets from source to destination. In contrast, LAR uses a route discovery mechanism which causes longer delays.

Delay of GSR is higher than GyTAR because packets whose delivery was suspended are stored in the buffer for longer time than in GyTAR's suspension buffer. Indeed, thanks to its more appropriate choice of routes, GyTAR uses less often its recovery mechanism and for smaller periods of time compared to GSR. B-GyTAR achieves a lower delivery delay than GyTAR, since in GyTAR with local recovery, packets that encounter local maximum will be stored in a buffer and carried by the vehicle, which may cause longer delays.

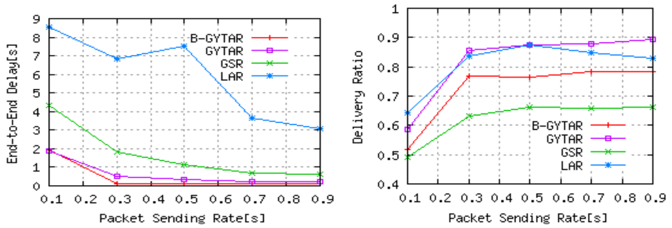
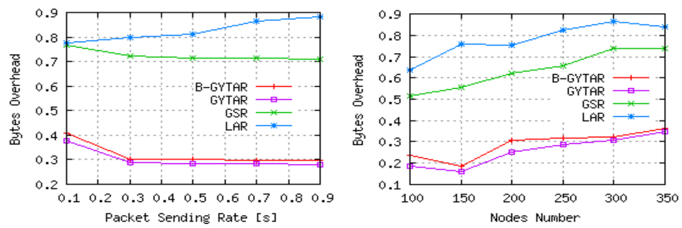


Figure 11. (a) End-to-end delay vs. Packet sending (300 nodes). (b) Delivery ratio vs. Packet sending rate (300 nodes)



(a)300 nodes, (b) 0.2 [s] (5 packets / second)

Figure 12. Routing overhead vs (a) packet sending rate, (b) number of nodes.

Routing Overhead: In Figure 12, we evaluate the routing overhead of the four protocols as function of data sending rate and vehicle density. Figure 12 (a) shows that the routing overhead of the studied protocols stays approximately constant for the different packet sending rates, since the overhead is mainly determined by the data delivered during the simulation as the number of nodes moving in the network is set to 300.

In Figure 12 (b), it is observed that the increase in the vehicle density leads to an increase in the routing overhead since the rate of control messages is proportional to the number of nodes. In general, B-GyTAR and GyTAR outperforms the two other studied protocols in all cases (i.e., when varying data transmission rates and also with different vehicle densities). This is expected since in both GyTAR variants, we have only the hello messages and the CDP as control messages which are sent periodically and are independent of topological changes. While in LAR, the control messages (Route Request, Route Reply, and Route Error) used for route discovery and route maintenance are sent frequently due to the rapidly changing topology of the network. Although GSR uses only 'hello' messages as control messages, it shows higher routing overhead than GyTAR. This is because GyTAR does not need as many hello messages sent as GSR to maintain its neighbouring table. This is due to the mechanism for neighbour's position inference used in GyTAR. Hence, the frequency of 'hello' messages recommended for GSR [19] is three times greater than the one needed by GyTAR.

VI. Conclusions

The GyTAR protocol, designed to operate optimally in urban environments, efficiently utilizes the unique characteristics of vehicular environments like the highly dynamic vehicular traffic, road traffic density as well as the road topology in making routing and forwarding decisions. The selection of intermediate intersections among road segments is performed dynamically and in-sequence based on the scores attributed to each intersection. The scores are determined based on the dynamic traffic density information and the curvemetric distance to the destination. The traffic density information for intersection score calculation is a decentralized mechanism in GyTAR to dynamically estimate nearly accurate vehicular traffic along traffic roads, with very low percentage of error. The optimum values for the weighting factors of the traffic density and distance information components in the intersection scores are evaluated and their sensitivity is analyzed showing a good balance between these two parameters. Simulation results show that GyTAR performs better in terms of throughput, delay and routing overhead compared to other protocols (LAR and GSR) proposed for vehicular networks. The robust intersection selection and the improved greedy carry-and-forward scheme with recovery, suggests that GyTAR should be able to provide stable communication while maintaining higher throughput and lower delays for vehicular routing in urban environments.

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Moez Jerbi received his M.S degree in computer engineering (honors) from INSA Lyon, and Ph.D. degree from the University of Evry, France in 2005 and 2008 respectively. From September 2005 to October 2008, he was working as research Engineer in Orange Labs - France Telecom R&D. He acted and still acts as a technical reviewer for several IEEE conferences and journals (ICC, VTC, VTM, PIMRC, etc). He has 4 granted patents and is author or co-author of over 20 journal and conference publications. His research interests include wireless Communications, mobile ad hoc networks and inter-vehicular communications. Moez is a member of IEEE.

Sidi Mohammed Senouci received in 1999 the M.S. degree from the University of Paris 13, France. In 2003 he obtained the Ph.D. degree in computer networks from the University of the Pierre & Marie Curie, Paris 6. From 2002 to 2004, he was an associate lecturer at the University of Cergy-Pontoise, France. From December 2004, he is Senior Research Scientist in Orange Labs. His current research interests include Vehicular Communications, Ad hoc and Sensor Networks, TCP over Wireless, Wireless and Mesh Networks, and Cooperative Networks. He published more than 50 technical journal and conference papers and holds several patents. He was the founding Chair of Ubiroads2007 workshop, and TPC co-chair of VehiCom2009 Workshop. He is founding co-editor of the IEEE ComSoc AHSN TC Newsletter. He also acted or still acts as TPC member of different IFIP, ACM or IEEE conferences and workshops. He is a Member of IEEE and the Communications Society.

Tinku Rasheed received his B.E. degree in electronics from Kerala University, India; his M.S. degree in Telecommunications from Aston University, Birmingham, U.K.; and his Ph. D. degree in computer networks from the University of Paris-Sud XI, Orsay, Paris, in 2002, 2004, and 2007 respectively. He was with Orange Labs in France, from May 2003 until December, 2006, where he was extensively involved in the development of routing protocols and QoS provisioning schemes for large scale heterogeneous mobile networks. Currently, he is a Senior Research staff member at Create-Net, Trento, Italy, where he is involved in several industry and European funded projects. He has 6 granted patents and is author or co-author of over 30 journal and conference publications.

Yacine Ghamri-Doudane is currently associate professor at the Ecole Nationale Supérieure d'Informatique pour l'Industrie et l'Entreprise (ENSIIE) - Evry, France. He received an engineering degree in

computer science from the National Institute of Computer Science (INI), Algiers, Algeria, in 1998, an M.S. degree in signal, image and speech processing from the National Institute of Applied Sciences (INSA), Lyon, France, and a Ph.D. degree in computer networks from the Pierre & Marie Curie University, Paris 6, France, in 1999 and 2003, respectively. His current research interests include Mobility Management in 4G Mobile Networks, Ad hoc and Sensor Networks, Vehicular Communications, TCP and Multimedia over Wireless, QoS in WLAN/WMAN, and Management of Wireless/Mobile Networks. He is also acting as ICC Selected Area in Communications Symposium Co-Chair in 2009 and 2010. Since December 2007, he is the Secretary of the IEEE ComSoc Technical Committee on Information Infrastructure (TCII). He is founding co-editor of the IEEE ComSoc Ad Hoc and Sensor Network Technical Committee (AHSN TC) Newsletter. He is a Member of IEEE and the Communications Society.