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iCAR-II: Infrastructure-based Connectivity Aware Routing in Vehicular Networks

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***Abstract*—With the high demand of mobile Internet services, Vehicular Ad hoc Networks (VANETs) become a promising technology to enable vehicular Internet access. However, the development of a reliable routing protocol to route data packets between vehicles and infrastructure gateways is still a challenging task due to the high mobility and frequent changes of the network topology. The conventional position-based routing (PBR) in VANETs can neither guarantee the existence of a routing path between the source and the destination prior to the transmission, nor provide connection duration information, which makes it unsuitable to route Internet packets. In this paper, we propose a novel infrastructure-based connectivity aware routing protocol, iCAR-II, that enables multi-hop vehicular applications as well as mobile data offloading and Internet-based services. iCAR-II consists of a number of algorithms triggered and run by vehicles to predict local networks connectivity and update location servers with real-time network information, in order to construct a global network topology. By providing a real-time connectivity awareness, iCAR-II improves the routing performance in VANETs by dynamically selecting routing paths with guaranteed connectivity and reduced delivery delay. Detailed analysis and simulation based evaluations of iCAR-II demonstrate the validity of using VANETs for mobile data offloading and the significant improvement of VANETs performance in terms of packet delivery ratio and end to end delay.**

I. NOMENCLATURE

i,j	Indices for vehicles, road segments, and intersections.
v_i	A vehicle with an identifier i.
R_i	A road segment with an identifier i.
I_i	An intersection with an identifier i.
R	The transmission range for line-of-sight cases.
$\hat{R}$	The transmission range for non-line-of-sight cases.
Loc_{v_i}	Cartesian coordinates of v_i location.
S_{v_i}	The reported average speed of v_i.
$ES^*_{v_i}$	The predicted average speed of v_i reported in a beacon message.
ES_{v_i}	The predicted speed of v_i stored in the routing table.
Sig_{v_i}	The turning signal status of v_i.
$RSSI_{v_i}$	The RSSI value of v_i.
$v_{i_{Table}}$	The routing table of v_i.
k_{v_i}	Vehicular density in front of v_i.
K_J	Traffic jam density in urban environment.
S_a	Averaged maximum speed.
f_{v_i}	A binary variable indicates if v_i is a *front* vehicle.
l_{v_i}	A binary variable indicates if v_i is a *leading* vehicle.
H_{v_i}	A binary variable indicates if v_i is moving towards a common intersection.
d	Distance between two vehicles.
MLL_{v_i}	Minimum predicted link duration with v_i.
RLL_{R_i}	Minimum predicted road-level connectivity duration for R_i.
$\mathbb{N}$	Set of neighbouring vehicles.
N	Set of potential forwarders.
$\mathbb{L}$,$\mathbb{F}$,$\mathbb{R}$	Sets of adjacent road segments representing *left*, *front*, and *right* road segments respectively.
$\mathbb{M}_{v_i}$	Set of vehicles between two control packet forwarders.
$\mathbb{L}_{v_i}$	Set of MLLs with vehicles $\in \mathbb{M}_{v_i}$.
$\mathbb{C}_{v_i,v_j}$	Set of common neighbouring vehicles between v_i and v_j.
$\mathbb{I}_{R_i}$	Set of two intersections bounding R_i.
P	Probability of initiating a road segment connectivity evaluation procedure.
$Last\_B$	Timestamp for the last mobility information update in the outgoing beacon messages.
τ_{Bt}	Time period for updating mobility information in the outgoing beacon messages.
$\tau_{LinkUpdate}$	Time period for updating neighbouring vehicles mobility information in routing tables.
$Last\_Upd_{v_i}$	Timestamp for v_i mobility information update.
ϵ_{vel}	Change in speed threshold to update a neighbouring vehicle's mobility information in routing tables.

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II. INTRODUCTION

Vehicular communication allows many appealing infotainment and traffic management applications that require Internet access. In VANETs, Roadside Units (RSUs) can work as Internet gateways for passing vehicles providing a low-cost drive-thru Internet [1]–[3]. With enabling multi-hop routing, vehicles forward Internet packets to extend the coverage of RSUs and Internet-based services [4]–[7]. This service, however, highly relies on the existence of forwarding vehicles and a reliable routing protocol. For sustainable and more reliable connectivity, stakeholders deploy cellular networks for in-car Internet access [8]. However, in dense areas with high vehicular traffic, and with respect to the explosive growth of mobile data traffic, the centric cellular networks can be easily overloaded. It is expected that the current mobile data demand will increase by 10 times and the monthly mobile data traffic will exceed 24 exabytes in 2019 [9]. Hence, using a hybrid network of VANETs and cellular network can support VANETs users with a more reliable low-cost Internet-based services, and enable mobile data offloading to mitigate the expected sever problem of cellular network overload.

One of the most challenging tasks to enable these features in VANETs is the design of routing protocols that cope with its highly dynamic topology. Unlike other networks, vehicles' high mobility and the frequent change of communication links between vehicles make the traditional topology-based routing protocols, such as AODV [10] and DSR [11], fail in VANETs as they flood the network with path finding and maintenance control messages [12]. Replacing this node-level network topology routing, an alternative geographical location-based routing paradigm, or position-based routing (PBR) has been introduced [12]–[14]. PBR depends on routing packets among geographical locations by arbitrary nodes instead of routing among pre-determined nodes. Studies confirm that this paradigm, PBR, outperforms topology-based routing in both urban and highway VANETs scenarios [12], [13].

PBR is a connectionless routing paradigm where a communication session is not required to be established before data transmission, and data packets are routed independently. Moreover, the existence of a routing path from the source to the destination during data forwarding and transmission is not guaranteed in PBR. To enable Internet access and mobile data offloading in a city VANETs, vehicles need instant information about connectivity to the core network before transmission. This information includes the existence of at least one routing path to an RSU gateway, in addition to the quality and the duration of the connection. Since PBR protocols do not support this information, a new routing paradigm, or an improved one, is required for Internet services in the heterogeneous network environment of VANETs and cellular networks.

In this paper, we propose a novel infrastructure-based connectivity-aware routing protocol, iCAR-II. iCAR-II deploys distributed algorithms to obtain real-time location and mobility information in order to estimate a minimum local network connectivity lifetime and experienced packet delivery delay per road segment, and updates location centers using cellular network channels. Thus, location centers can construct a city-level dynamically updated network view, or a real-time network topology, and support inquiring senders with up-to-date connectivity information, routing paths to gateways, and destination locations. With this global connectivity-awareness, iCAR-II significantly improves VANET performance and enables efficient mobile data offloading via RSUs.

The contribution of this work can be summarized as following: 1) Introducing a heuristic methodology to obtain a minimum communication link duration between each pair of communicating vehicles ; 2) Introducing another methodology to obtain a road segment-level minimum connection duration; and 3) proposing a distributed and dynamic position-based routing protocol that utilizes the introduced methodologies for efficient data routing and manages a cooperative operation between cellular networks and VANETs. The remainder of this paper is organized as follows. Section III gives insight into related work. Section IV describes the system model under consideration. The details of the proposed routing scheme is presented in Section V, followed by analysis and simulation-based performance evaluation in Section VI. In Section VII, we provide concluding remarks.

III. Related Work

Using multi-hop VANETs routing for Internet access and mobile data offloading is a recent research focus and only few works have considered its various challenges. [2], [3] and [15] study Internet access in VANETs. In [2], the throughput of drive-thru Internet is studied considering one-hop vehicle-to-infrastructure scenario. In [3], a Chain Cluster scheme is presented for a cooperative content download and distribution among vehicles passing RSUs on highways. In [15], a strategy for RSUs placement is designed to enable multi-hop Internet access. Moreover, [16] and [17] consider data offloading in the vehicular environment. In [16], challenges and possible solutions of offloading vehicular and cellular data traffic via drive-thru Internet are presented, while [17] provides an analytical study to evaluate the potential of VANETs for cellular traffic offloading.

For the routing challenge in VANETs, many protocols have been proposed. One of the leading protocols that deploys PBR for mobile environment is GPSR [18]. GPSR uses *Greedy forwarding* where packets are forwarded to nodes that are closer to the destination. When this strategy fails, GPSR uses *Perimeter forwarding* as a recovery strategy, where packets are forwarded around the perimeter of the failing region. In addition to the geographic location required by GPSR, other protocols [4], [14], [19]–[21] consider the availability of further network information for better routing performance. GSR [14] is an intersection-based routing that uses street maps and source routing, where the shortest path, by the means of intersections, is attached to each packet. A-STAR [19] uses a statistically rated map for street-traffic aware routing. TIGeR [20], GyTAR [21], and iCAR [4] deploy real-time vehicular traffic information for traffic aware intersection-based routing, where routing decisions are made at intersections based on local vehicular traffic information obtained from each road.

Most connectivity-aware routing protocols relate vehicular traffic density with connectivity, and tend to select dense roads in routing paths for better network connectivity. Only few works consider studying key connectivity metrics, such as link duration and connection lifetime, for urban VANETs routing. [22] presents a prediction model to estimate link duration between two communicating vehicles considering relative speed, inter-vehicle distance, and the impact of traffic lights. In [23], a framework to analyze the network connectivity of urban VANETs based on link duration, connectivity duration, and re-healing time is provided. The framework considers relative velocity, traffic lights, and turning vehicles as the main causes of link breakage. In [24], a link duration estimation method is presented using cross-layer metrics. Physical layer information is used for better link duration estimation and long lifetime route construction in VANETs.

IV. System Model

The network model considers a city scenario with a heterogeneous network of VANET and the 4G cellular network, LTE, as well as a set of location servers on the core network forming Location Centers (LCs) as shown in Figure 1. City roads segments are bidirectional with variable length, width, and vehicle densities. Roads segments are bounded by either controlled or uncontrolled intersections. VANET consists of mobile vehicles equipped with On Board Units (OBUs), and RSUs along roads. OBUs have GPS receivers and can extract vehicles locations and velocity vectors. OBUs have access to

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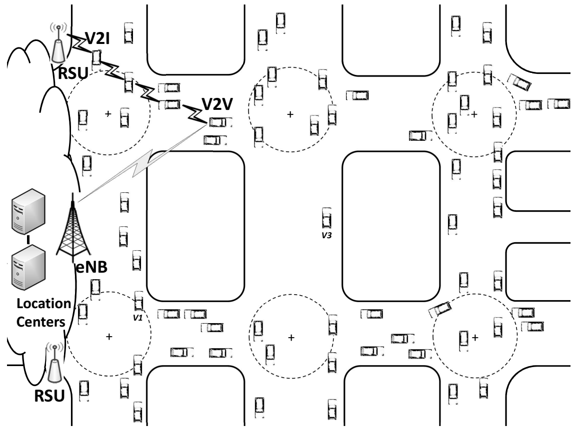

Fig. 1. Network Model

vehicles' turn-signals and are equipped with LTE interface for cellular communication and synchronization purposes. RSUs are partially deployed and do not provide full coverage to road segments, however, multi-hop forwarding is enabled to extend their coverage. Vehicles participate in multi-hop forwarding using their own OBUs, i.e., have sufficient inducements to forward packets belonging to other vehicles. RSUs work as gateways to infrastructure and both RSUs and LTE eNBs have access to LCs, e.g., via IP/UDP Internet protocols. All network entities use identical digital maps with well-defined roads and intersections.

In iCAR-II, vehicles frequently update LCs with their locations and local network status as described in Section V. These updates are sent to LCs either via LTE channels or RSUs. Vehicles also periodically broadcast their locations, mobility vectors, and network status information (NSI) to their one-hop neighbours. LCs maintain tables of vehicles locations; a vehicle updates its location periodically or whenever it enters a new road segment. Moreover, LCs construct a dynamic network topology consisting of road segments weighted by experienced packet delivery delay. Whenever a source vehicle has packets to transmit via the infrastructure, it chooses either to send via VANET or LTE, based on the available network connectivity information. If VANET disconnection is reported, the source either selects LTE mobile data or reschedules the transmission. If such information is not available, a source transmits an inquiry message to LCs via LTE to obtain network status along with the best route.

Infrastructure in the system consists of VANETs RSUs, LTE eNBs, and LCs servers. RSUs work as VANETs gateways to the core network. With respect to the deployment cost, higher RSUs deployment results in better VANETs connectivity and shorter routing paths. When connectivity to an RSU is not confirmed, LTE channels support VANETs routing with the following: Updating vehicles locations at LCs, updating local (road-level) connectivity information at LCs, and obtaining NSIs from LCs. Thus, LTE communication overhead depends on VANETs connectivity to the core network and the efficiency of iCAR-II to proactively confirm this connectivity. Location centers play an important role in this design. They receive huge amount of updates, maintain updated network topology and vehicles locations, and respond to vehicles' inquiries. However, LCs can consider a design of distributed location servers that matches the geographically distributed nature of VANET. For example, a city-road map can be divided into a number of vicinities and each server be responsible for one or more of these vicinities. Adjacent vicinities can exchange their real-time road-level network topology to have a wider network view, and a proper hierarchical server architecture will enable obtaining any destination location in the network. The details of LCs physical design such as map division and servers' management and allocation are out of this paper's scope, and LCs will be considered as one logical unit in the system hereinafter.

V. iCAR-II Infrastructure-based Connectivity Aware Routing

iCAR-II is a PBR routing scheme designed for multi-hop vehicular infotainment applications and Internet-based services as well as mobile data offloading. The principal of iCAR-II scheme is to support vehicles with instant information about VANET connectivity to infrastructure. Vehicular applications can, accordingly, decide to use VANET or LTE channels to access the core network. In order to achieve this principal, iCAR-II considers a number of algorithms and procedures run by vehicles' OBUs and LCs:

1) Beaconing and neighbourhood awareness
2) Mobility-based link lifetime estimation between each pair of neighbouring vehicles
3) Road segment connectivity estimation
4) City-level network topology construction and data routing

For safety purposes, vehicles are required to periodically report road and driving conditions to nearby vehicles [8], [25]. This is achievable by VANETs' one-hop broadcast *beaconing* messages, which also includes vehicles location and mobility information. Using beacon information, vehicles estimate local connectivity lifetime with one-hop neighbouring vehicles and achieve local neighborhood connectivity awareness. Beacons also help to exchange Network Status Information (NSI) which includes connectivity status to infrastructure, route to an RSU, and expected expiry time for that route. It will be shown later that routes in iCAR-II are represented by intersection IDs, and therefore, routes to infrastructure are different at different roads. Thus, NSIs are exchanged locally within road segments while vehicles at intersections might receive NSIs from different roads.

When a vehicle, v_i, enters a road segment, R_j, it initiates, with a probability P, a measurement procedure called Road Segment Connectivity Evaluation (RSE) by sending a unicast control packet (CP) that transverses the road segment to the other end, collecting some connectivity information from forwarders' routing tables. When failing to reach the destination intersection, CP is dropped due to local network disconnection, and a random backoff time is set in NSI. Otherwise, a vehicle at the other end reports the minimum expected connectivity lifetime of R_j and the experienced delivery delay of CP to LCs via LTE channels. The LCs'response, that

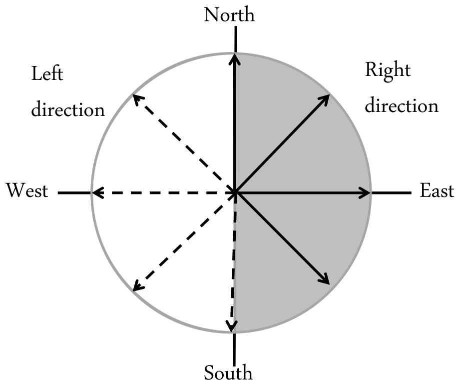

Fig. 2. Defining Driving Directions

includes one or more routes to RSUs as well as a route lifetime, is attached in a beacon message and broadcasted to vehicles on R_j.

When a vehicular application or mobile data user needs to access the core network, or a non-neighbouring vehicle, via iCAR-II, it either finds a valid route in NSI or sends an inquiry message to location centers via LTE. LCs locate the target destination, run a shortest-path algorithm, (e.g., Dijkstra) on part of the graph that includes both the source and destination, and send back an NSI message to the source. LCs include a number of RSUs in the source vehicle vicinity in its search in order to select the best route and suggest alternative routes. Upon receiving NSI with a valid route, the source starts the low cost VANETs communication for the specified period of time, and refreshes path information before the expiry time of the current path if needed. In following, we describe the different stages of iCAR-II in more details.

A. Beaconing and Neighbourhood Awareness

Every vehicle is required to broadcast road conditions periodically to its one-hop neighbours, to enable several safety applications. These messages are used by PBR in VANETs as beacons, or network heart beats, to support the awareness of a vehicle's existence, location, and communication channel status within the communication range. In addition to road and driving conditions, vehicles in iCAR-II are required to include some essential information to enable its functionality. Information includes: 1) vehicle identifier (v_{ID}), 2) vehicle location coordinates (Loc_{vID}), 3) average driving speed (S_{vID}) for the last m seconds, 4) driving direction (Dir_{vID}), 5) turning signal status (Sig_{vID}), and 6) the predicted effective speed ES_{vID} which is a function of S_{vID} and average speed of leading vehicles (LS_{vID}) as will be shown in the next section. Leading vehicles are the group of neighbouring vehicles located in front of a transmitting vehicle, moving in the same road segment and direction, and having the same turning signal status. Leading vehicle average speed is easily calculated using information from the vehicle's routing table, $v_{ID_{Table}}$.

Each road segment is bounded by two intersections, has a unique identifier (R_{ID}), and has two possible opposite directions. A vehicle is considered to be moving in a left (right) direction if it is heading any direction from north/south to west (east) as shown in Figure 2. Turning signal variable (Sig_{vID}) can take one of three values representing two signalling directions, *Right* and *Left*, and an *Idle* status.

The routing table is a table that is maintained by each vehicle to store neighbouring vehicles' information. In addition to routing information reported in beacons, $v_{i_{Table}}$ includes fields to track received signal strength indication ($RSSI_{vID}$), timestamps of last recorded entries and row update ($Last\_Upd_{v_{ID}}$), the estimation of minimum communication link lifetime (MLL_{vID}), a binary variable l_{vID} to indicate if the vehicle belongs to the leading vehicles group, and another binary variable f_{vID} indicating if v_{ID} is located in front of v_i at the updating moment regardless of its mobility direction and turning signal.

$v_{i_{Table}}$ is maintained by: adding new row information when receiving a beacon from a newly arrived vehicle to the communication range, updating row information when a beacon message is received from a neighbouring vehicle, deleting a row information from the table when no beacon is received from a current neighbour for a certain period of time τ_{delete_row}, and updating l_{vID} and f_{vID} values with periods of time τ_{l_update} and τ_{f_update} respectively. Row entries for an individual neighbour v_{ID} are updated periodically upon receiving a beacon message from v_{ID} with an acceptable $RSSI$ and a period of $\tau_{LinkUpdate}$. τ_{delete_row}, τ_{l_update}, τ_{f_update} and $\tau_{LinkUpdate}$ are much larger than the inter-beacon interval in order to reduce $v_{i_{Table}}$ maintenance operations. In addition, a neighbouring vehicle's information is updated if the difference between the reported predicted speed in the received beacon, ES^*_{vID}, and the recorded predicted speed in $v_{i_{Table}}$ exceeds a certain speed threshold ϵ_{vel}, or if the remaining time before the expiry of MLL_{vID} is less than ϵ_{MLL} as described in Algorithm 1.

Similarly, the routing information for a vehicle v_i is updated in the outgoing beacons periodically with respect to the timestamp of the last update, $Last\_B$, and a threshold value τ_{Bt} to control the frequency of updating this information. Routing information in outgoing beacons are also updated upon detecting a change in NSI.

B. Mobility-based Link Lifetime Estimation

Finding the minimum link lifetime (MLL) between two vehicles based on their mobility information exchanged in beacons is an imperative component within iCAR-II. Based on mobility prediction, MLL is defined as the expected remaining time duration for two communicating vehicles to stay within the communication range of each other before the first possible link breakage occurs due to their mobility, i.e., before the distance between them is predicted to exceed R meters due to a possible mobility scenario. Many vehicular mobility models can be applied in order to predict MLL, e.g., Car Following Models [26]. In this paper, we consider a unique prediction model that takes into consideration the actual requirements for iCAR-II as a routing protocol, as well as the information available at, or derived from, beacons and routing tables. The MLL-prediction model considers the following factors:

1) Relative Location: Which includes the relative distance, d, between two communicating vehicles, v_i and v_{ID}, in

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Algorithm 1 Beaconing

if Sending a Beacon **then**
  if $|Current\_time - Last\_B| \geq \tau_{Bt} \|$ New NSI has been received **then**
    Obtain S_{vi}, LS_{vi}, Sig_{vi}, Dir_{vi}
    Update routing information in the Beacon
  else Reuse routing information
  end if
  Prepare a Beacon message with v_{ID}, road/driving status, routing information, timestamp
  Send the Beacon message for broadcasting
end if
if Receiving a Beacon **then**
  if $RSSI_{vID} \geq RSSI_{threshold}$ **then**
    Extract v_{ID}
    if $v_{ID} \notin v_{i_{Table}}$ **then**
      Add v_{ID}, Find $MLL_{v_{ID}}$, and Complete v_{ID} entries in $v_{i_{Table}}$
    else Set $Last\_velocity = ES_{vID}$ (table value)
      Set $Crrnt\_velocity = ES^{*}_{vID}$ (beacon value)
      if $|Crrnt\_velocity - Last\_velocity| \geq \epsilon_{vel} \| Current\_time - Last\_Upd_{vID} \geq \tau_{LinkUpdate} \| MLL_{vID} \leq \epsilon_{MLL}$ **then**
        Find MLL_{vID} using recent information
        Update v_{ID} entries in $v_{i_{Table}}$
      end if
    end if
  end if
end if

addition to the road segments that v_i and v_{ID} belong to. v_i and v_{ID} can either belong to the same road segment, R_{v_i}, or to two adjacent road segments, R_{v_i} and $R_{v_{ID}}$. Two adjacent roads have a common intersection, and accordingly, R_{vID} can be described to be to the right, in front, or to the left of R_{vi}. Thus, at each road, the set of adjacent road segments can be divided into three subsets, $\mathbb{R}$, $\mathbb{F}$, and $\mathbb{L}$, according to the orientation of v_i and the common intersection, regardless of driving direction.

2) Vehicles Speed: The *Predicted Effective Speed* ES_v is introduced in order to mitigate the effect of the frequent change in vehicle's speed and acceleration in the city environment driving pattern. The predicted speed for a vehicle v_j, ES_{vj}, is a function of both the vehicle's average speed in the last m seconds, S_{vj}, and the average speed of its leading vehicles, LS_{vj}, and also depends on the density of leading vehicles in front of it as follows:

$$d_L = \begin{cases} d_I, & \text{if } R > d_I \\ R & \text{else} \end{cases} \tag{1}$$

$$k_{vj} = \frac{1}{d_L} \cdot \sum_{i=1}^{N} l_{vi} \tag{2}$$

$$LS_{vj} = \begin{cases} \frac{1}{\sum_{i=1}^{N} l_{vi}} \cdot \sum_{i=1}^{N} S_{vi} \cdot l_{vi}, & \text{if } \sum_{i=1}^{N} l_{vi} > 0 \\ 0 & \text{else} \end{cases} \tag{3}$$

$$ES_{vj} = \begin{cases} (1 - \frac{k_{vj}}{k_J}) \cdot S_{vj} + \frac{k_{vj}}{k_J} \cdot LS_{vj}, & \text{if } k_j < k_J \\ LS_{vj} & \text{else} \end{cases} \tag{4}$$

where d_I is the distance between the vehicle and the next intersection based on its mobility direction, d_L is the distance that leading vehicles occupy, k_{vj} is the leading vehicles traffic density ($vehicle/m$), and k_J is the traffic jam density.

3) Driving Direction: Each vehicle is aware, by the means of beacons, of the driving direction of itself and its neighbouring vehicles within the same road segment, i.e., either the same or the opposite driving direction. For neighbouring vehicles belong to adjacent road segments, and with respect to their driving direction and common intersection, I_j, the binary variable H_v is defined as follows:

$$H_{v_{ID}} = \begin{cases} 1, & \text{if } v_{ID} \text{ is heading to } I_j \\ 0 & \text{else} \end{cases} \tag{5}$$

H_{vID} information of each neighbouring vehicle, v_{ID}, that belongs to a different road segment can be maintained in the vehicle's routing table. In addition, turning signal information, Sig_{vID}, gives another key indication for prospective driving direction.

Between two neighbouring vehicles v_i and v_{ID}, each combination of the previous variables (i.e., $R_{v_{ID}}$, $H_{v_{ID}}$, H_{v_i}, $Sig_{v_{ID}}$, Sig_{v_i}, $f_{v_{ID}}$) defines a unique *Case*. Accordingly, iCAR-II mobility prediction model defines 144 possible cases. Each *case* is studied to predict one or more potential mobility *Scenarios* between the communicating vehicles. Then, each *scenario* is further studied to derive a corresponding equation to obtain MLL. First, the different scenarios are defined according to the following rules and assumptions:

1) For a vehicle v_i, neighbouring vehicles within the same road segment, and those belonging to a *front* road segment ($R_{vID} \in \mathbb{F}$) are considered to be moving in one dimension; on the other hand, neighbouring vehicles belonging to a *right* or *left* road segment ($R_{vID} \in \{\mathbb{R} \bigcup \mathbb{L}\}$) are considered to be moving in a perpendicular direction to v_i.
2) A neighbouring vehicle, v_{ID}, within the same road segment that has an idle turning signal maintains its speed of ES_{vID} for the prediction period.
3) Three mobility scenarios are studied for each vehicle, v_{ID}, that has an active turning signal: moving in the same driving direction with the speed of ES_{vID}, stopping at the reported location (waiting to make a turn), and making an instant change of direction according to Sig_{vID} and moving at the *Averaged Maximum Speed* S_a. S_a is a constant that considers an initial speed of 0 m/s and a maximum acceleration, until reaching a maximum speed, for a total travel distance of R meters.
4) When the communicating vehicles v_i and v_{ID} belong

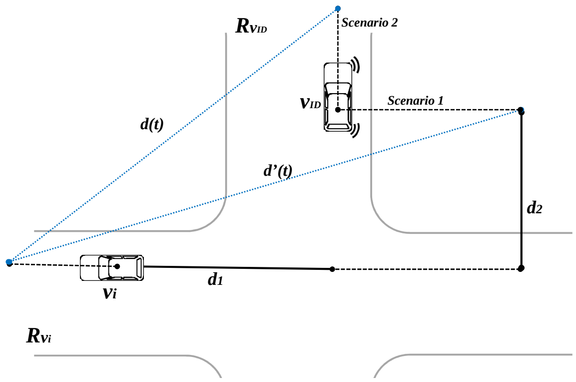

Fig. 3. An Example Case with Two Mobility Scenarios

to different road segments, and v_i is moving towards the common intersection, two additional scenarios are considered: instant stopping of v_i (due to a red traffic light) and proceeding of v_i at the speed of S_a.

5) In scenarios where vehicles move in perpendicular directions or where instant change of vehicle's driving direction is considered, a reduced effective transmission range $\hat{R}$ is used to represent a non-line-of-sight communication environment.
6) When there are more than one mobility scenarios for a certain case, only the scenario/scenarios that can cause earlier communication disconnection is/are considered. If the first disconnection depends on the actual values of the case variables in more than one scenario, equations from the different scenarios are considered, and MLL takes the minimum result. The predicted MLL might be obtained from a different scenario than the actual one, or from a misinterpreted turning signal, i.e., an active turning signal for a lane change only. This can result only in a shorter MLL, and is corrected via the frequent MLL updates as shown in Algorithm 1 to maintain valid MLL information.
7) The prospective mobility scenario is predicted for a short period of time to insure the validity of the given mobility information; thus, MLL is upper-bounded by R/S_a.

The aforementioned rules determine one or more mobility scenarios for each case under consideration. Each scenario is associated with a predicted link lifetime, t, between the communicating vehicles. To obtain t, a corresponding equation to each scenario is derived as follows:

1) A diagram for the potential mobility scenario is created; a case example for mobility in two dimensions is presented in Figure 3 with two potential mobility scenarios.
2) According to the aforementioned rules and a certain scenario under consideration, the different variables of the scenario are determined, e.g., using R, $\hat{R}$, S_a, ES_v etc.
3) For mobility in one dimension, simple Kinematic equations are used to find t. For example, for a scenario of two vehicles moving towards each other with predicted speeds ES_{vi} and ES_{vID}, and with an initial distance d between them, we would have:

$$t = (R + d)/(ES_{vi} + ES_{vID}) \tag{6}$$

4) For mobility in two dimensions, the Parametric equations for the predicted trajectory of each vehicle are defined with respect to the parameter t, i.e., defining $x_{vi}(t)$, $y_{vi}(t)$, $x_{vID}(t)$, and $y_{vID}(t)$ as functions in time. Then, the Pythagorean theorem is used to find the predicted change in distance between the communicating vehicles $d(t)$:

$$d(t) = \sqrt{(x_{vi}(t) - x_{vID}(t))^2 + (y_{vi}(t) - y_{vID}(t))^2} \tag{7}$$

By substituting $\hat{R}$ for $d(t)$ and solving for t to find the required link lifetime, we obtain an equation associated with the mobility scenario to predict MLL. For example, considering *Scenario 1* in Figure 3, the variables under consideration are $\hat{R}$, d_1, d_2, ES_{vi}, and S_a. The parametric equations for this scenario are: $x_{vi}(t) = -d_1 - ES_{vi}t$, $y_{vi}(t) = 0$, $x_{vID}(t) = S_a t$, and $y_{vID}(t) = d_2$. By applying the Pythagorean theorem:

$$d(t) = \sqrt{(-d_1 - ES_{vi}t - S_a t)^2 + (-d_2)^2} \tag{8}$$

Replacing $d(t)$ by $\hat{R}$ and solving for t in the case that $\hat{R} \geq d$:

$$t = \begin{cases} \frac{-d_1 + \sqrt{\hat{R}^2 - d_2^2}}{S_a + ES_{vi}} & \hat{R} \geq d \\ 0 & \hat{R} < d \end{cases} \tag{9}$$

Similarly, the different scenarios have been studied for the different cases and a set of equations have been determined. When a vehicle v_i needs to update the value $MLL_{v_{ID}}$ in $v_{i_{Table}}$ upon receiving a beaconing message from v_{ID}, v_i determines the mobility case based on the available information and calculates the predicted link lifetime t. When more than one scenarios are considered, the minimum value of t is maintained. Then, the minimum link lifetime between v_i and v_{ID} is updated in $v_{i_{Table}}$:

$$MLL_{v_{ID}} = min(t, \frac{R}{S_a}) \tag{10}$$

$MLL_{v_{ID}}$ is updated frequently at $v_{i_{Table}}$ with respect to three criteria, as shown in Algorithm 1: 1) periodically with a period of $\tau_{LinkUpdate}$, 2) if a major change in v_{ID}'s predicted speed has been detected, and 3) if v_i is receiving beacon messages, with acceptable $RSSI_{v_{ID}}$, after, or close to, the expiry time of the expected MLL_{vID}.

C. Road Segment Connectivity Evaluation

Road segment evaluation (RSE) is a heuristic procedure dynamically initiated by some vehicles to sense the different parts of the network and update the network status information NSI. NSI includes road segment connectivity to infrastructure (RSU) status, the best route to infrastructure, the expected packet delivery delay via that route and the expiry time of it. NSI is shared locally within a road segment and exchanged via beacon messages. In RSE, a light-weight control packet CP traverses the road segment via relaying forwarders and collects connectivity and link lifetime information at each intermediate forwarder. When reaching the target intersection I_{ID}, a vehicle v_j at I_{ID} reports the connectivity status of R_{ID}

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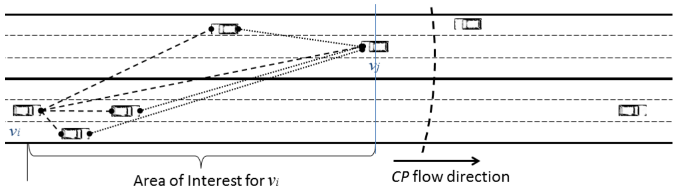

Fig. 4. Calculating RLL in Road Segment Evaluation

and its predicted minimum link lifetime $RLL_{R_{ID}}$ to LCs via LTE, and obtains an updated $NSI_{R_{ID}}$ accordingly.

RSE procedure is initiated, with a probability P, by a CP originator v_i entering a road segment R_{ID} towards an intersection I_{ID}. The principle of RSE is predicting a minimum link lifetime per road segment based on link lifetime information, $MLLs$, between individual vehicles available at their routing tables. RSE divides R_{ID} into smaller vicinities, or areas of interest (AoIs), between CP forwarders as shown in Figure 4. While passing CP, each forwarder finds the maximum link lifetime between itself and the previous forwarder, directly or via one-hop relay vehicle. The originator and each forwarder, v_{lf}, attaches in CP the set $\mathbb{L}_{v_{lf}}$ which includes MLLs values for all neighbours in its AoI along with their identifiers' set $\mathbb{M}_{v_{lf}}$. A receiver forwarder, v_{cf}, extracts the set of common neighbours $\mathbb{C}_{v_{lf},v_{cf}}$ and finds the maximum possible link between itself and the last forwarder, $RLL_{v_{lf},v_{cf}}$, as indicated below:

$$\hat{l}_{max} = \max_{v_i \in \mathbb{C}}(min(MLL_{v_{lf},v_i}, MLL_{v_{cf},v_i}) \tag{11}$$

$$RLL_{v_{lf},v_{cf}} = max(\hat{l}_{max}, MLL_{v_{lf},v_{cf}}) \tag{12}$$

Intermediate forwarders update $\mathbb{M}$ and $\mathbb{L}$ while keeping only the minimum value of $RLL_{R_{ID}}$. The last CP receiver, v_j, which is the closest to I_{ID}, reports the total delivery delay of CP, $D_{R_{ID}}$, along with $RLL_{R_{ID}}$ to LCs. LCs update the network graph, find the route(s) to RSU(s), and send $NSI_{R_{ID}}$ back to v_j. Then, v_j unicasts the updated NSI to CP originator and broadcasts it via its beacons. Every vehicle within R_{ID} updates $NSI_{R_{ID}}$ and includes it in its beacons.

As greedy routing without store-carry-forward is used to deliver CP, reaching I_{ID} indicates local network connectivity at R_{ID} for a period of time registered in CP. The delivery delay of CP also gives an indication of packet delivery delay in the road as it experiences similar transmission and queuing delay in addition to interference and fading conditions in R_{ID}. For a disconnected road segment, CP is dropped when a forwarder, or an originator, v_i fails to find a next forwarder. v_i creates an NSI indicating disconnectivity with a small random validity period, which works as a back-off time to prevent multiple RSE calls by vehicles entering R_{ID}.

When v_i enters R_{ID}, it is expected to receive an NSI from its neighbours, which includes the expiry time of NSI. To ensure the availability of a valid NSI, P is designed to be a function of the remaining validity time of $NSI_{R_{ID}}$, t_{rem}, and R_{ID} length $|R_{ID}|$. When v_i does not receive any valid NSI, it also initiates the RSE procedure. Equations 13 and 14 present one way to design P [7]:

$$P = \begin{cases} e^{-\frac{t_{rem}-C}{2}}, & t_{rem} \geq C \\ 1 & t_{rem} < C \end{cases} \tag{13}$$

$$C = 2 \cdot t_{max} \cdot \lceil |R_{ID}|/R \rceil + \epsilon \tag{14}$$

where t_{max} and ϵ are design constant parameters representing the maximum acceptable delay per forwarder, including average transmission delay and queuing delay, and the expected time to obtain NSI from LC, respectively.

D. City-level Network Topology and Data Routing

The frequent distributed calls of the RSE procedure and the associated connectivity and delay information sent to LCs, enable LCs to draw a real-time network graph providing a city-level network topology awareness, where the graph consists of vertices, representing road intersections, and weighted edges, representing road segments where each edge is weighted by the experienced delay. As LCs receive RSE update messages for only connected roads, the graph represents only real-time network view of the map, and edges with expired validity lifetime can be removed. With a known set of RSUs locations in a city, each road segment has a subset of nearby RSUs; thus, after receiving an RSE update message related to a certain road R_{ID}, a shortest path algorithm, e.g., Dijkstra, is run on the subgraph of the network that has the road segment R_{ID} and the subset of nearby RSUs to find the best route to the core network. LCs send back a response message to the sender, which has an NSI. Then, the sender broadcasts the NSI in R_{ID} via beacons, which enables connectivity awareness to all vehicles in the vicinity of R_{ID}. NSI includes the path, by the means of intersections, the path's lifetime, which is the minimum $RLL_{R_{ID}}$ among road segments constructing the path, and the expected delivery delay, which is the summation of experienced delivery delay for road segments constructing the path.

According to the direction of data forwarding, either towards RSU or a destination vehicle, data routing can be described as uplink routing or downlink routing. For uplink routing, vehicles that have data to send find connectivity and expected delay information available in NSI. According to this information, vehicles either use VANETs, LTE, or reschedule transmission for better VANETs conditions. In the case of a connected network, the path from a source road segment to a destination RSU is predetermined by the means of consecutive intersections. Thus, iCAR-II deploys source PBR where the path is attached to the header of each packet, which reduces cost, delay, and overhead of multiple route enquiries via LTE. In case a packet has reached a disconnected road, a forwarder can encapsulate the packet and forward it via a new path using a more recent NSI available at its road segment, if any, otherwise the packet is dropped. Disconnection can occur due to an unexpected delivery delay beyond the path lifetime, or an unexpected local network disconnection in the routing path during its lifetime. On the other hand, vehicle's location, an associated RSU, and the path from RSU to the vehicle, by the means of intersections, are determined by LCs in the downlink routing case. Data packets are forwarded from the

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Algorithm 2 Next-hop Selection

Require: $v_{cf_{Table}}$, R_{vcf}, I_{Crnt_Target}, I_{Nxt_Target}, $RSSI_{threshold}$

for z= 1 to $|\mathbb{N}|$ **do** (check all neighbours)
  if $R_{vz} == R_{vcf} || I_{Nxt\_Target} \in \mathbb{I}_{R_{vz}}$ **then**
    if (v_{cf} moving towards I_{Crnt_Target} & $f_{vz} == 1$) || (v_{cf} moving away from I_{Crnt_Target} & $f_{vz} == 0$) $|| I_{Nxt\_Target} \in \mathbb{I}_{R_{vz}}$ **then** (v_z makes forwarding progress)
      if $RSSI_{v_z} \geq RSSI_{threshold}$ **then**
        $\mathbf{N} = \mathbf{N} \cup v_z$ (v_z is a potential forwarder)
      end if
    end if
  end if
end for
if $\mathbf{N} \neq \phi$ **then**
  Find v_{nf} $s.t.$ $d_{v_{nf}} = max(d_{v_z} \forall v_z \in \mathbf{N})$
else
  Next-forwarder is not found (packet will be dropped)
end if

core network to the RSU, and VANETs data routing takes place from RSU to the destination vehicle using source PBR.

For routing within roads, iCAR-II uses a greedy-based next-hop selection method. Algorithm 2 shows a light-weight next-hop selection procedure to filter one-hop neighbours based on their location and the latest received $RSSI$. The location filter in the forwarding process aims to maximize the progress towards the target intersection. Such greedy forwarding protocol selects next-forwarders that are farther from a sender, which are more likely to leave the communication range causing transmission interruption, or have bad signal quality. Thus, $RSSI$ filter excludes neighbours with $RSSI$ below a certain threshold. A vehicle's mobility direction is not considered in order to maximize the number of potential forwarders, taking into consideration that vehicle's mobility can be negligible compared to data transmission speed, and the distance between vehicles are updated frequently on routing tables.

While forwarding data packets, a next forwarder v_{nf} is chosen only from the current road segment, or the road segment connecting to the next target intersection I_{Nxt_Target} in the packet's path. When a packet reaches the last road segment in its path, each forwarder v_{cf} looks up the packet's destination in its routing table. In Algorithm 2, $\mathbb{I}_{R_{vz}}$ defines the set of two intersections that bounds the road segment R_{vz}.

VI. Performance Evaluation

This section presents the evaluation of iCAR-II. First, the individual components of iCAR-II are considered in brief analysis and discussion. Then, the overall performance is evaluated using a special MATLAB-based simulation program developed to evaluate VANETs routing protocols performance. In addition to iCAR-II, we considered three other VANETs routing protocols, which have been slightly modified in order to have a fair comparison with iCAR-II, i.e., having the same infrastructure resources. In the following, we present the evaluation methodology, the simulation setup, the evaluation metrics for comparing the different protocols, the protocol components analysis, and the analysis of simulation results.

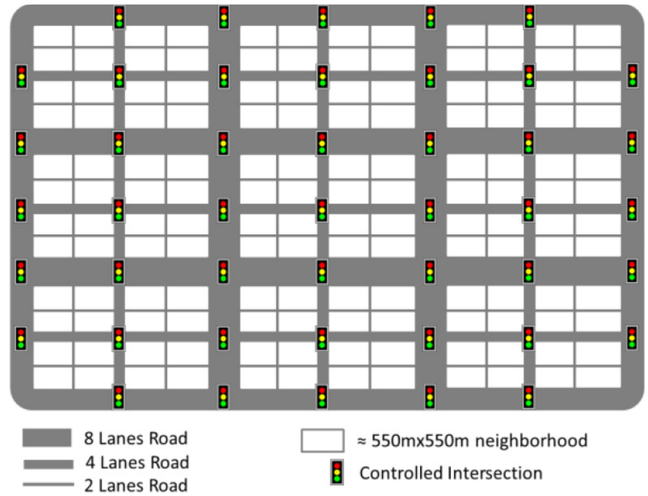

Fig. 5. Approximate simulation map

A. Evaluation Methodology

We first study the different components of iCAR-II, namely:

- Beaconing and neighbourhood awareness
- Node-Level Link Lifetime
- Road-Level Connection Lifetime
- City-Level Network Connectivity
- Location Service and Data Routing,

then, we compare the performance of iCAR-II with three common PBR protocols:

- GPSR [18], which is a MANET protocol used widely as a performance benchmark for geographic routing protocols.
- GSR [14], which is a VANETs PBR protocol and it uses source intersection-based routing.
- GyTAR [21], which is another PBR VANETs intersection-based routing protocol that takes into consideration vehicular traffic. GyTAR has been also deployed widely for comparing routing performance in the VANETs context.

Those protocols are modified to use LTE channels to report vehicles location periodically and acquire the location of the destination, or the closest RSU, from LCs.

B. Simulation Setup

VANETs city scenario has been implemented in MATLAB to represent 7000 $m \times$ 7000 m grid area of bidirectional roads. Roads vary in terms of length, width, and vehicles density to represent major roads and residential areas in the city. Each road segment has a predefined maximum speed. Figure 5 shows approximate map that represents the roads grid which has a total of 165 intersections, with 45 of them being traffic-light controlled. The open-source microscopic vehicular traffic generator SUMO [27] is used to generate vehicles movement files. SUMO uses car-following model and the input of our grid map including the number of lanes and traffic densities.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Scenario Duration	40 s	$RSSI_{thrrdhold}$	0.6x$RSSI_{max}$
Scenario Repetition	5-12 times	τ_{Bt},$\tau_{deletrow}$,	
		$\tau_{lupdate}$,τ_{fupdt},	
R	250 m	$\tau_{LinkUpdate}$,	3 s
		m	
$\hat{R}$	150 m	ϵ_{vel}	7 m/s
Packet Size	512 $Byte$	S_a	15 m/s
Transmission Rate	12 $Mbps$	K_J	0.4 vehicle/m
Packet Lifetime	1500 ms	C	1.5 s

For wireless consideration, a simple DCF MAC is applied for MAC contention, a FIFO packet queue, such as the AC queues design for WAVE's MAC layer [28], is implemented for packet buffering, and a free space model with urban area path loss exponent [29] [30] is deployed for $RSSI$ estimation. Source vehicles are randomly selected, where source vehicles are always 10% of the total number of vehicles for the different vehicles density scenarios. Each source vehicles continuously sends data packets to the core network via RSUs, where packets are routed independently. LTE channels are assumed to have ideal communication and represented by a fixed delay of 200 $msec$ for one-way communication. Fetching information from LCs is also represented by a fixed delay of 500 $msec$. Each simulation scenario has been repeated several times for accurate results. Table I presents the general simulation parameters used in this evaluation.

C. Evaluation Metrics

The performance evaluation of the routing protocols has considered variable network density, packet generation rate, and number of deployed RSUs. The performance metrics are:

- Packet Delivery Ratio (PDR): we define two forms of packet delivery ratio to show the ability of a routing protocol to successfully transfer data from a source to a destination on an end-to-end basis: 1) PDR1: number of successfully received data packets by destinations per number of sent data packets per sources, and 2) PDR2: number of successfully received data packets by destinations per the total number of data packets sent, or ready to be be sent, at sources.
- Average Packet Delivery Delay (PDD): This metric shows the latency of data packet delivery introduced by each routing protocol and defined as the average end-to-end delivery delay of all successfully delivered data packets.
- Average Routing Overhead: This metric shows the extra communication overhead required by routing protocols. Two types of routing overhead are defined: 1) average LTE routing messages, e.g., location updates and enquiry messages, per second, and 2) average unicast routing control packets which is the average of extra unicast packets sent by vehicles to maintain the routing protocol per second per road segment.

D. Simulation Results

1) Beaconing and Neighbourhood Awarness: Beaconing is one of the main components in any PBR protocol. Beaconing rate can be either fixed or dynamic with respect to speed, vehicle density, or other parameters. Since we have considered a fixed beaconing rate in this study, any other beaconing scheme is still valid as long as it enables iCAR-II to predict MLLs and exchange NSIs. iCAR-II considers two strategies to reduce the computation and communication overhead that can occur to update MLLs and share NSIs. First, instead of updating MLL value for each neighbouring vehicle upon receiving its beacon, iCAR-II reduces the number of MLL updates for each neighbour per second by the factor of $1/\tau_{LinkUpdate}$. Simulation shows that the effect of updating MLL values on the iCAR-II performance is negligible if the $\tau_{LinkUpdate}$ is less than 3 sec. Second, iCAR-II uses beacons to share NSIs in order to preserve the bandwidth.

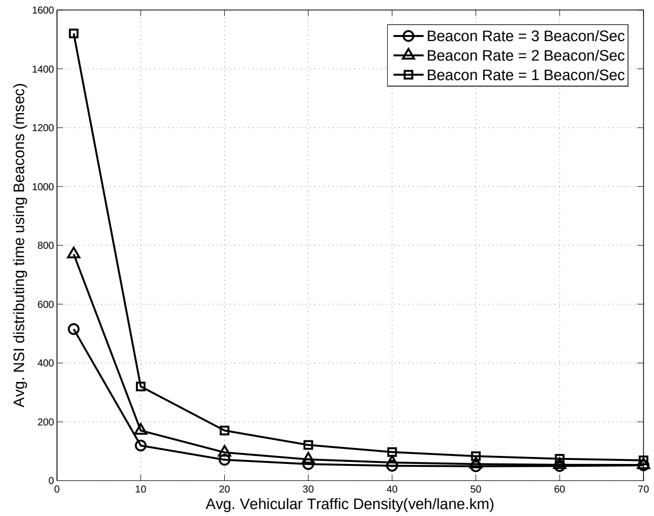

Fig. 6. Average delay for network information dissemination within a road segment using beacons

Figure 6 shows the delay required to deliver NSI to all vehicles within a road segment of 1 klm length and 4 lanes width. It is shown that NSI distribution time is generally decreased by the increased vehicular density and/or beaconing rate. In light and moderate traffic densities, increasing vehicular density or beaconing rate significantly decrease the delay to deliver NSI. However, in dense areas, and with high static beaconing rate, the delivery of beaconing packets is delayed due to packets' collisions, or rescheduling, causing slightly delayed NSI delivery. Thus, NSI delivery delay in such situations highly depends on the performance of the deployed MAC protocol. In general, results in Figure 6 show acceptable delay taking into consideration that Equations 13 and 14 preserve time for NSI delivery.

2) Node-Level Minimum Link Lifetime: The MLL finding procedure predicts the worst possible case scenario for future movement of two neighbouring vehicles based on their mobility vectors, distance between them, distance to a common intersection, and their turn-signal status, in order to assign a lower-bound of link lifetime between them. MLL is frequently updated, while vehicles are exchanging beacons, every $\tau_{LinkUpdate}$. Simulation results show that this procedure succeeds in putting a lower-bound of link lifetime in all cases.

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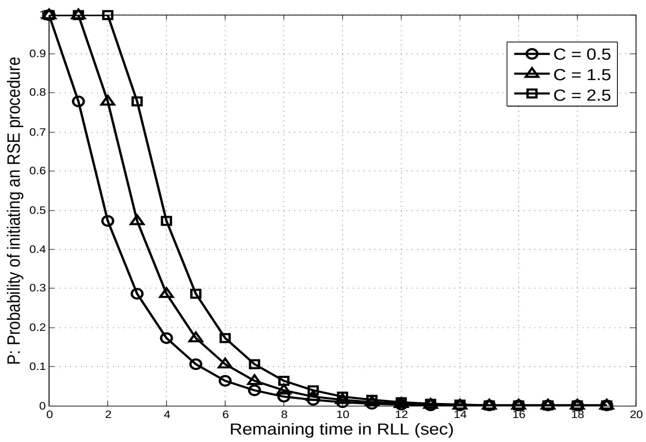

Fig. 7. Probability of initiating RSE procedure for a vehicle entering the road segment

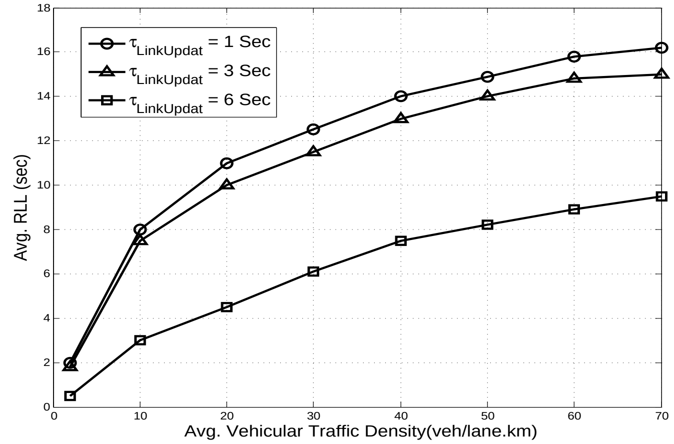

Fig. 8. Average RLL in a road segment

In other words, it successfully predicts link breakage before it happens. However, in real-life situations, other cases can occur causing link breakage within the predicted minimum lifetime. For example, a parking vehicle on the side of the road can have a high MLL value; however, it is more likely to turn-off its OBU causing a communication termination. Such situations represent a small percentage and can be ignored.

Equations 1 to 4 present the expected speed ES of vehicles based on its average speed and the average speed of its leading group. Differentiating between leading vehicles based on their turn-signal status makes ES more accurate. The mean percentage error of ES prediction, with $\tau_{LinkUpdate}$ defined in Table I, is 4.3%. However, with large $\tau_{LinkUpdate}$ value, this mean increases significantly, considering urban scenario with controlled intersections where drivers change their speed frequently due to traffic lights status. To avoid the effect of such error when using larger $\tau_{LinkUpdate}$ values, Algorithm 1 calls MLL procedure when a major change in speed is detected.

3) Road-Level Minimum Connection Lifetime: Minimum road connectivity lifetime algorithm is a heuristic algorithm that uses the link lifetime information available at nodes' routing tables to assign a minimum road-level link lifetime (RLL) to each road segment. First, one possible routing path is considered to check instantaneous connectivity, then one-hop relay between each pair of consecutive forwarders in the path is considered to predict future connectivity. Among each pair, the maximum predicted link lifetime is selected, and among the selected set, the minimum link lifetime is considered to be the RLL. Intuitively, the road segment has at least one connected path from end-to-end during RLL second. More than one initial path can be considered, and more than one-hop possible intermediate relay can be calculated, which increase the predicted RLL. However, this increase comes at the cost of communication overhead to share more than one-hop neighbouring MLL information, and calculation overhead to find all possible future links among those vehicles. However, iCAR-II considers only the previously calculated one-hop MLL, available at vehicles' routing tables, along with dynamic updating procedure using P in Equation 13. P is able to maintain valid RLL while the road segment has a connected path. It takes into consideration the time required to generate RLL and obtain and distribute NSI, before the expiry time of the current one.

Figure 7 shows the probability of initiating an RSE call by a vehicle entering the road segment as a function of RLL's remaining time considering different values of C. C is a design parameter related to road length, transmission range, maximum acceptable transmission time per one-hop, and the time required to obtain NSI from LCs. Figure 8 shows the average reported RLL values with respect to different vehicles density. It shows that even with low vehicles density, roads can maintain connected paths for a considerable duration of time, and RSE procedure enables source vehicles to instantaneously utilize these paths. Moreover, the results show that the average RLL is directly proportional to vehicles density within road segment. This can be related to the decrease in average vehicles speed in the high density scenario as well as the availability of more intermediate nodes between each pair of CP forwarders. RLL is also inversely proportional to $\tau_{LinkUpdate}$ as with large $\tau_{LinkUpdate}$ values, the remaining time of MLLs decrease before updates, and RLL decreases accordingly.

4) City-Level Network Connectivity: iCAR-II is a proactive protocol that enables vehicles to have immediate global network condition information by making NSIs available at vehicles' beacons. Vehicles, via NSI, can know about the road connectivity to the core network, the route to an RSU, the expected delivery delay, and the expiry time of that route. Routes are dynamically updated on LCs by probabilistically initiating RSE procedures among different network edges. LCs maintain updated network values as Equations 13 and 14 insure that.

Figure 9 shows the percentage of connected road segments to the infrastructure with respect to different network node densities and number of deployed RSUs. It can be seen that iCAR-II can construct connected networks even with low deployment of RSUs. This can be related to the global view of connected road segments at LCs. With respect to road segments length, number of lanes per road segment, and the transmission range under consideration, it is shown that the number of connected road segments to the core

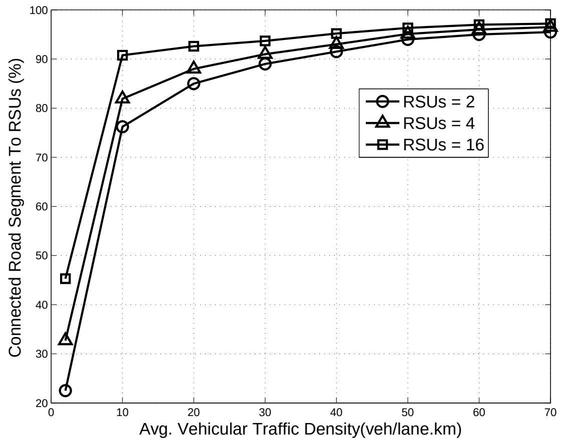

Fig. 9. Percentage of Connected Road Segments to the Core Network using *iCAR-II*

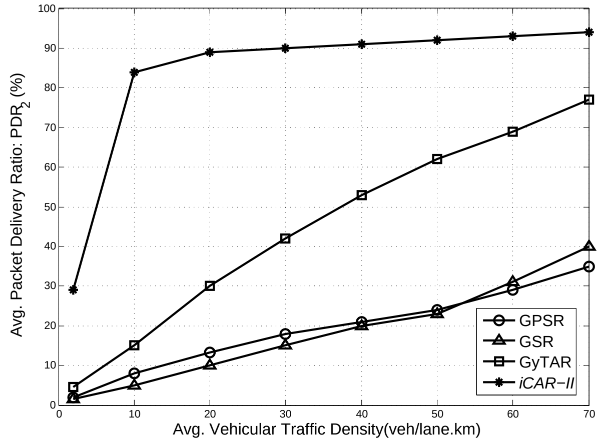

Fig. 10. Average Packet Delivery Ratio ($PDR2$) using 4 RSUs and PGR = 10 packet/sec

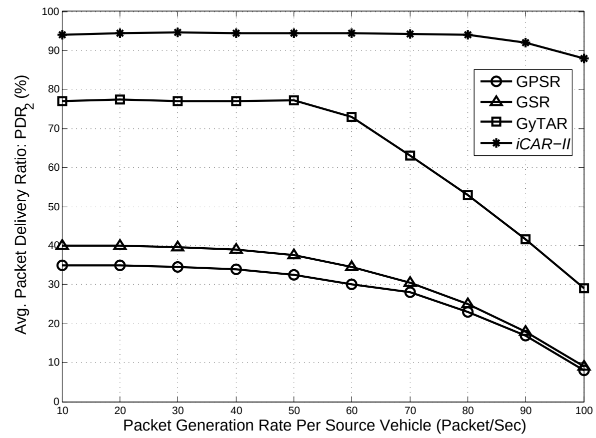

Fig. 11. Average Packet Delivery Ratio ($PDR2$) using 4 RSUs and vehicle density of 70 vehicle/lane.klm

network is increasing rapidly with the increase in vehicular density in the light traffic densities test points (less than 10 $vehicles/lane.km$) as the network connectivity becomes more sensitive to vehicular densities in this range. With higher vehicular densities, the increase becomes slower as most main roads are already connected to RSUs and only few roads are joining the network when increasing the number of vehicles.

5) Packet Delivery Ratio: As packets are transmitted by source vehicles using iCAR-II only when connected path is detected, the ratio of delivered data packets to the sent packets (PDR1) is expected to be high regardless of network node density. With PGR = 10 packets/sec and the deployment of 4 RSUs, simulation shows that PDR1 always exceed 97%. Data packets that have not been delivered during the lifetime of the path might be dropped due to an expected network disconnection. Also, packets that have not been delivered during their lifetime due to delivery delay are dropped. Notice that iCAR-II conserves network bandwidth by buffering data packets when VANETs is not connected to the core network.

In order to have a valid performance comparison between iCAR-II and GPSR, GSR, and GyTAR, which do not require prior determination of path existence before transmission, we define PDR2 to be the ratio of packets successfully delivered to packets that are ready to be sent. Figures 10 and 11 show that iCAR-II still has a significantly higher PDR2 than the other PBR protocols. Figure 10 shows that increasing vehicles density, with a low data packet traffic in the network, improves packet delivery ratio, as VANETs become more connected. With low vehicles densities, GPSR, GSR, and GyTAR show a very low PDR2 as they blindly route data packets through an intermitted network, while iCAR-II has a noticeably high PDR2 due to its connectivity awareness feature. The curve trend of iCAR-II is analogous to the network connectivity curve in Figure 9. Data packets might be routed along paths that are not the shortest curvemetric routes yet connected. It is observed that GSR performs better than GPSR only in high vehicular density, when VANETs are connected, as GSR does not consider vehicular traffic in the routing decision. In high vehicular densities, GPSR suffers from higher routes length compared to other protocols as it does not use map information or anchor routing. In such cases, GPSR packets reach their expiry time before delivery.

Figure 11 shows PDR2 of the different protocols with respect to a variable PGR and a high vehicular density. Results show that iCAR-II maintains high performance even with an increasing PGR. As iCAR-II considers delivery delay per road segment in its route constructing level, new paths are dynamically suggested by LCs to maintain network performance. On the other hand, GSR does not consider dynamic routing while GPSR and GyTAR considers only local connectivity and distance to destination, which result in routing convergence to dense roads, which causes data traffic congestions and high queuing delay. Delay is associated with PDR as delayed packets can reach their expiry time before delivery and be dropped. The slight dropping in iCAR-II PDR2 shown in Figure 11 with high PGR is due to reaching the communication capacity of RSUs.

6) Packet Delivery Delay: As iCAR-II considers packet experienced delivery delay of CPs a major metric in route calculation, average packet delivery delay (PDD) using iCAR-II is expected to be low. Simulation results show that iCAR-II significantly reduces PDD compared to other routing protocols as shown in Figures 12 and 13. With low vehicle densities, iCAR-II selects connected paths even with long trajectories to achieve higher PDR with the cost of slightly high PDD. PDD of GSR is analogous to that of iCAR-II in the case of light

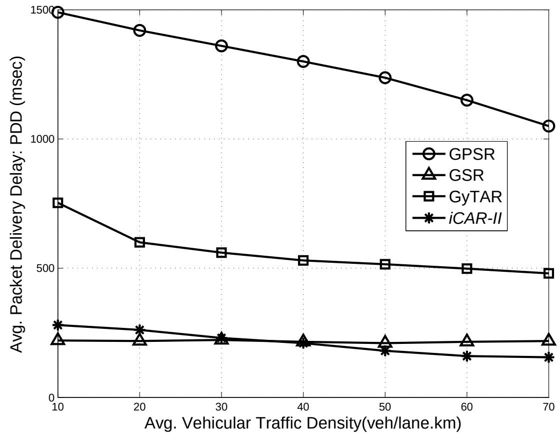

Fig. 12. Average Packet Delivery Delay (PDD) using 4 RSUs and PGR = 10 packet/sec

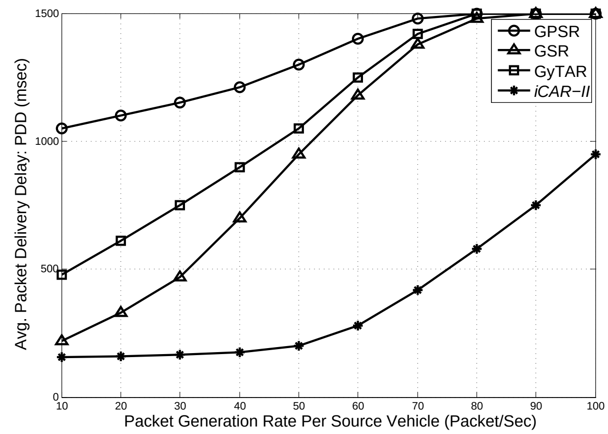

Fig. 13. Average Packet Delivery Delay (PDD) using 4 RSUs and vehicle density of 70 vehicle/lane.klm

data traffic as packets are routed along predetermined paths. However, these paths are either connected to the core network or the packets are dropped, causing very low GSR-PDR as shown in Figure 10.

Simulation results also show that PDD in GPSR is high. Packets forwarded using GPSR encounter a high number of intermediate forwarders due to the perimeter recovery routing strategy and the experience of long routing paths. Moreover, increasing PGR leads to a significant PDD increase in GPSR, GSR and GyTAR, as shown in Figure 13. These protocols do not consider delivery delay in its routing, and when routes converge to a limited number of roads, data traffic congestion increases the delivery delay. It can be shown from Figure 11 and 13 that a considerable portion of data packets have been dropped due to reaching their expiry lifetime, which is set to be 1500 $msec$ in our study. As iCAR-II uses dynamic route selection considering the experienced delivery delay, it has a significantly reduced PDD.

7) Routing Overhead: We consider the additional routing control messages to measure and compare the introduced overhead by the different routing protocols. These control packets can be classified into three categories: 1) Beaconing messages; 2) LTE routing messages; and 3) Unicast routing control messages. Beacons are the main communication overhead introduced by any PBR protocol, as the broadcast beaconing messages use control channels periodically. However, beacons are required by safety applications, and as long as different protocols use the same inter-beacon interval/beaconing protocol, the effect of beacons on the networks is the same for the different protocols.

LTE communication overhead is an important evaluation metric, as accessing LTE channels cost more than VANETs DSRC channels. Figure 14 shows the simulation results of average LTE control messages used for each vehicular density scenario. In GSR and GyTAR, LTE routing messages are used to report entering new road segments (location updates) and to enquire about a destination location. iCAR-II has a slightly higher average of LTE control messages as it uses LTE channels to update road condition information. In GPSR, vehicles use LTE channels for location updates and location inquiry messages. The average LTE communication overhead, when

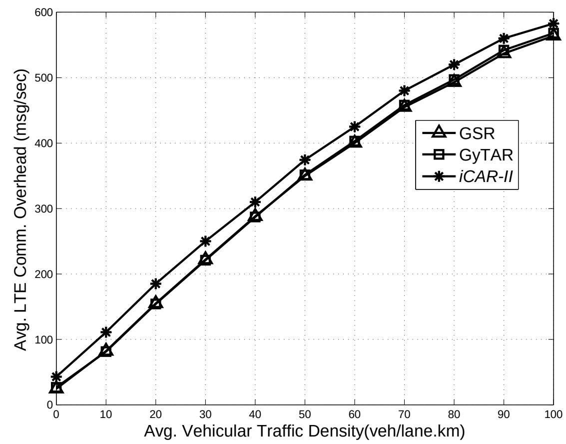

Fig. 14. LTE Routing-Control Messages

GPSR is deployed, depends on the location update period, and it is always higher than the average overhead generated by the other protocols.This shows one of the advantages of intersection-based routing.

To better understanding the LTE communication overhead, Figure 15 shows the average number of LTE control messages sent by each vehicle per hour. It is shown that iCAR-II introduces higher LTE overhead specially in the sparse network cases. In fact, the increase of LTE overhead in iCAR-II as compared to the other protocols is still insignificant with respect to the increase in PDR shown in Figure 10. In the worst case, the difference is about 60 messages per vehicle per hour, which is a small cost to obtain connectivity information in a sparse network for data offloading or VANETs Internet access. With higher vehicle densities, roads become more connected with higher average RLL and less LCs updates accordingly.

The third type of communication overhead for routing control is the unicast packets sent locally within roads to collect traffic information in GyTAR and to examine connectivity, collect links lifetime and calculate delivery delay in iCAR-II. Although iCAR-II introduces about double the number of these control packets compared to GyTAR, this overhead can be neglected as these packets are unicast, distributed, and in the worst case the average number of control packets does not exceed two packets per second for each road segment.

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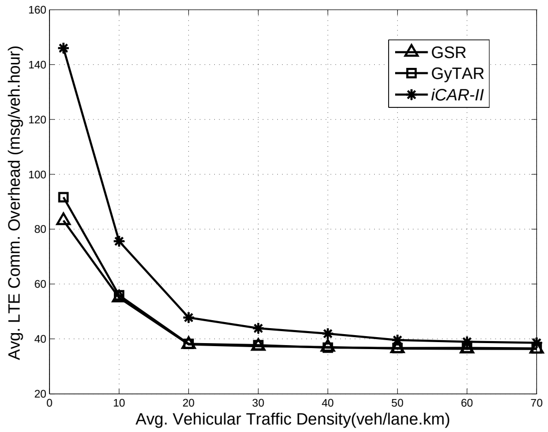

Fig. 15. Average LTE Routing Messages per Vehicle per Hour

VII. Conclusions

In this paper, an efficient framework, iCAR-II, has been introduced to integrate VANET, cellular network, and location centers, in order to improve VANETs data routing and enable cellular network mobile data offloading. iCAR-II enables mobile users to proactively obtain VANET connectivity to the core network information. The availability of this information preserves VANET's bandwidth, in the cases of disconnectivity or data traffic congestions, and enables users to enjoy the low-cost VANET-based Internet access and mobile data offloading. iCAR-II utilizes the reliable communication channel of cellular network to construct a global real-time view of VANET's topology. It has been demonstrated that iCAR-II algorithms can provide real-time VANET information to mobile users, and an efficient and dynamic data routing, with a limited use of LTE messages per vehicle. With respect to the current framework, RSUs placement can be optimized in order to increase VANETs connectivity to the core network and reduce the cost of RSUs deployment, which will be considered in our future work.

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