2016 12th Annual Conference on Wireless On-demand Network Systems and Services (WONS)

LTE Floating Car Data application off-loading via VANET driven clustering formation

Pierpaolo Salvo*, Ion Turcanu*, Francesca Cuomo*, Andrea Baiocchi* and Izhak Rubin†
*DIET at University of Roma “Sapienza”, Rome, Italy
†Electrical Engineering Department, UCLA, Los Angeles, CA, USA

***Abstract*—Floating Car Data (FCD) applications are based on the collection of geo-localized information updates that are issued by vehicles roaming in a given area. These data are an essential source for traffic information and are widely employed by Intelligent Transportation Systems (ITS). We present and examine a hybrid networking architecture and protocol that are used for the efficient execution of such a collection process. We employ a VANET-based multihop dissemination logic to spread control messages and elect designated nodes. Those nodes are exploited to report vehicular data via LTE communications. The performance behavior of the proposed protocol is evaluated through the consideration of two real urban scenarios. In comparing with performance bounds that characterize the performance behavior attained by state-of-the-art hybrid integrated VANET and LTE mechanisms, we show our approach to offer a substantial reduction in the traffic load rates induced over the LTE cellular radio access system.**

***Index Terms*—VANET; LTE; IEEE 802.11p; dissemination; data collection; Floating Car Data**

I. INTRODUCTION

Floating Car Data (FCD) are an essential input to an increasing number of applications in the context of the Intelligent Transportation System (ITS) [1][2]. Under the ETSI definition of Cooperative Awareness Basic Service [3], Cooperative Awareness Messages (CAMs) are exchanged among vehicles to promote and maintain vehicular system awareness among vehicles and to support cooperative interactions among networked vehicles that roam the roads. Such messages provide positional information, as well as identify the status of neighboring vehicles. A vehicle can then learn the status of vehicles that can be reached through a single wireless communications hop from itself. Using CAMs, each vehicle records and updates a Local Dynamic Map (LDM). An LDM is a local database maintained by each On Board Unit (OBU) where information collected about *neighboring* vehicles are stored. Due to vehicles' mobility, this information is periodically updated through the exchange of CAMs.

Despite the recommendation made in 2011 of using the IEEE 802.11p [4] protocol as the standard for vehicular communications, in recent years many researchers and industrial organizations have considered using the LTE cellular network as an alternative solution for vehicular networking applications, specifically for the transport of Floating Car Data message flows.

LTE-centric transport mechanism have been investigated, where FCD are collected from vehicles directly, by using on-board LTE radio modules. The same LTE network is then also used to disseminate this information in an area of interest. [5] gives a detailed evaluation of LTE uplink and downlink traffic load generated by specific ITS applications, including FCD collection for vehicular traffic monitoring. In [6][7] VANET and LTE technologies are compared, identifying the strengths and weaknesses of these two approaches under different conditions (vehicular density, vehicular speed, transmission rate). On the opposite side, VANET based traffic data collection has also been investigated (e.g., see [8][9]). An intermediate approach is represented by the employment of a heterogeneous network paradigm, identified also as a Hybrid Wireless Network [10][11][12][13]. The latter integrates the use of LTE cellular wireless communications technology with the IEEE 802.11p based VANET.

The $LTE4V2X$ system presented in [10] uses LTE technology to create clusters of vehicles. The latter are subsequently managed by using an IEEE 802.11p based VANET networking operation. A similar approach is adopted in [11], where the Authors study the impact of the vehicular data collection in an LTE network. In this paper, the cluster head selection process is managed by the base station node (eNodeB), making use of LTE communications channel quality indicators measured and reported by each vehicle. The authors show that such a system is able to reduce the negative impact of FCD transmissions on the quality of communications transport of conventional LTE traffic. In [12], the proposed hybrid solution entails the selection of the cluster head on the basis of different LTE parameters. Finally, in [13], the authors propose a centralized system for creating clusters and for electing cluster heads. The clustering process is performed here by a remote server, assuming it to have a much wider regional view of the system, when compared with the limited scope available to a single eNodeB.

In this paper, considering an urban scenario, we present a hybrid networking mechanism under which a VANET based vehicle-to-vehicle dissemination protocol is employed for the purpose of supporting LTE based FCD collection operation. The aim is to reduce substantially the number of concurrently active LTE channels and the information message load carried across the LTE cellular network. We employ a distributed procedure that exploits the ”horizontal” capability of vehicles to communicate among themselves via the VANET based V2V channels, to elect *representative nodes*. These nodes are responsible for communicating aggregated FCD via the LTE infrastructure. The performance gains achieved through the use

ISBN 978-3-901882-80-7

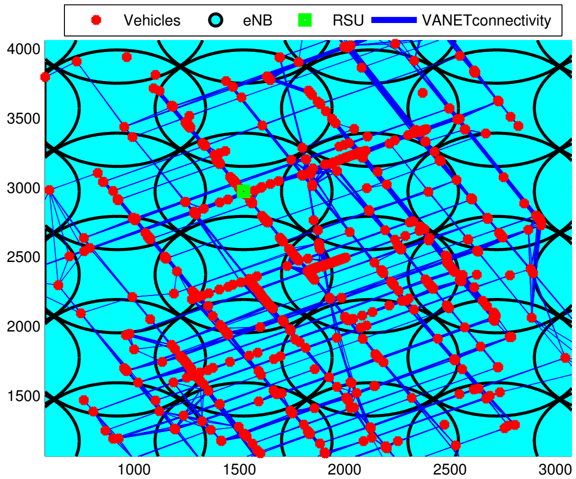

Fig. 1. Monitored urban area covered by LTE macro-cells; the red dots denote vehicles and the blue lines connecting them highlight active VANET links (Manhattan, NY).

of the proposed approach rapidly increase as the vehicular density increases. Under such high density conditions, the traffic loading of the LTE cellular network can become critically high, while VANET networking connectivity improves. Under low vehicular density levels, our procedure falls back onto the use of a plain LTE-based FCD collection scheme. The employed operation and protocols rely on the use of geographical information known individually by each vehicle (e.g., via GPS), not requiring the use of external databases (such as those that make use of urban city maps and junction proximity sensors).

The rest of the paper is structured as follows. The innovation and complementarity of our approach with respect to other hybrid VANET and LTE procedures, that have been published to date, is discussed in Sec. II. The details of the proposed protocol are defined in Sec. III. The simulation model used in the performance evaluation of the proposed approach is described in Sec. IV. In Sec. V, we present illustrative performance results. Conclusions are drawn in Sec. VI.

II. HYBRID VANET-LTE FLOATING CAR DATA COLLECTION SCENARIO

We consider an urban area scenario covered by one or more LTE macro-cells. FCD updates originated by vehicles moving in the underlying coverage area, are collected continuously over time and fed to a number of ITS related applications. Conceptually, we think of the collected FCD as processed by a backhaul server, referred here to as *FCD processing server* (FPS). The placement of the FPS (in a remote data center or close to the monitored area, possibly even co-located with an LTE node) is immaterial to the ensuing discussion. The relevant point is that FCD collected from the monitored area, often encompassing more than a single LTE macro-cell, are processed together, thus exploiting jointly the information collected over the entire monitored area.

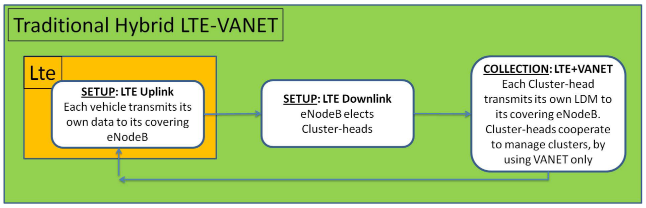

Fig. 2. LTE and Hybrid LTE-VANET FCD collection schemes in the existing proposals.

Vehicles are assumed to be equipped with On Board Units (OBUs) supporting LTE, IEEE 802.11p, plus a GPS device. Vehicles generate, send and receive Cooperative Awareness Messages (CAMs) periodically, as described by the ETSI standard. The CAM exchange is conducted through the 802.11p VANET operation over its dedicated bandwidth [4]. By receiving CAMs, each vehicle creates its own Local Dynamic Map (LDM). In this manner, it is aware of the states of other vehicles in its neighborhood area, including their time-stamped positions, velocities, moving directions, basic attributes and other basic sensor information.

A. *State-of-the-art approaches*

FCD can be collected directly via LTE, by requiring that each vehicle sends its own data periodically via an individual LTE channel. The resulting load could become massive [14][15], so that even ad hoc planning of the LTE RAN could be required [14]. Hence, it makes full sense to exploit the bandwidth resource assigned to V2V Dedicated Short Range Communications (DSRC) via the IEEE 802.11p VANET. All state-of-the-art proposal based on a hybrid LTE plus VANET networking infrastructure follow a common paradigm, where two main algorithmic phases can be recognized: i) SETUP; ii) COLLECTION (Fig. 2).

The SETUP phase aims at gathering status information involving vehicles that roam in the target area, and making this information available to the FPS. This information is then used to set up, in an optimal fashion, the process governing the mode of operation to be used during the ensuing FCD collection phase. Proposed techniques published to-date envision an operation during the SETUP phase under which *each vehicle* communicates the relevant data *individually* to the FPS, via LTE connections.

During the COLLECTION phase, the vehicular population is split into clusters. *Cluster head* vehicles are elected based on the information collected during the SETUP phase. The choice of cluster head can be the outcome of an optimization problem that takes into account: i) information on vehicles' positions, velocities and directions; ii) VANET connectivity information (neighbors of each vehicle, according to the received CAMs); iii) information on the CQI of LTE channels measured by the vehicle on board units. A centralised optimization approach, run in the FPS, can be used to identify the best candidate equipped vehicles for the role of cluster-head nodes. The cluster heads are then designated at the end of SETUP phase, before the start of the ensuing COLLECTION phase, by sending control messages on the LTE downlink channels that cover the target area.

A cluster head is responsible for collecting FCD from its one-hop neighbouring vehicles via VANET wireless links. The latter vehicles form its cluster. The cluster head then forwards the collected data to the FPS, using its LTE connections. In this manner, only cluster heads (rather then each vehicle) use LTE channels. The collection of FCD is repeated periodically over the duration of a COLLECTION phase.

The SETUP phase is also repeated periodically. The topological layout of cluster heads and their election operations are thus adapted to new system conditions, refreshing the information required to optimally synthesize the layout and operations governing the ensuing COLLECTION phase. The COLLECTION phase continues in an uninterrupted manner until it is determined that the current cluster layout deviates beyond a margin level from a currently calculated optimal configuration; a new SETUP phase is then triggered. The duration of the COLLECTION phase is therefore tied to the scope and features of the monitored area and to the dynamics of the vehicular traffic roaming the area.

B. *Our proposed approach*

The number of used LTE channels can be reduced by using only specifically designated nodes to employ LTE channels for the purpose of transporting update data to the FPS. Each such designated node would aggregate and forward data that represents the status of vehicles in its immediate neighborhood. This status data stored in the LDM is available at each vehicle, as each one continuously collects such data through the maintenance of a background CAM exchange process.

The key idea is that such designated nodes can be identified by executing a dissemination-like process across the vehicular wireless network (VANET). The dissemination networking logic provides for the multihop transport of messages across the vehicular network through the election of certain nodes (i.e., vehicles) to act in forwarding a received message to other vehicles. By definition, the dissemination logic implies the designation of special nodes (the message *forwarders*), that *make up a connected set of nodes, covering the area spanned by the VANET*. Then, the dissemination logic is used to elect *designated nodes*, identified as the forwarding nodes. The designated nodes are employed as local collection points that are used for sending FCD information obtained from neighboring vehicles to the FPS via LTE. They can do so by sending their respective current LDM databases. The utility of the dissemination procedure increases as the vehicular density increases, as the demand for LTE wireless connections is then much higher and thus becomes a critical resource issue.

The above approach can be used to aggregate the information to be sent uplink via LTE during the SETUP phase. Alternatively, the dissemination-like logic can be designed to elect designated nodes that act *directly* as cluster heads. This way, the SETUP and COLLECTION phases are collapsed into a single phase, driven by a "horizontal" process that makes use of the VANET dissemination process to elect designated nodes. The election process used to elect designated nodes is re-run periodically, or when needed.

Summing up, our proposed VANET based election mechanism can be used to replace the SETUP phase employed by existing hybrid VANET+LTE solutions. It can also be used to work as a new, stand-alone procedure that is used to realize the FCD collection process. The key elements that motivate our use of the proposed mechanism are:

- We take advantage of utilizing the dedicated spectrum bands assigned for VANET services to reduce the traffic loads imposed on the LTE wireless access network.
- Our proposed mechanism can be realized in a manner that is fully compliant with currently realized technology and standards (e.g., by using the CBF algorithm of the GeoNetworking protocol [16] as the dissemination-like logic).
- The LTE network, and other future cellular networks, can offer message transport at much higher communications rates. Cell sizes are becoming smaller and high inter-cell interference effects become dominant. The latter limit the attainable system throughput efficiency level. It is consequently more effective to employ a lower number of nodes for the forwarding of larger amounts of data aggregates, instead of a large number of sources of relatively small amounts of data.

In the next Section, we provide a detailed description of our proposed algorithm.

III. THE VANET BASED PROTOCOL FOR THE ELECTION OF REPRESENTATIVE NODES

A. *The dissemination logic*

Vehicle-to-vehicle multi-hop communications enable the extension of the road span covered by Road Side Units (RSUs) or On Board Units (OBUs) which act as data sources. Such a V2V multihop dissemination function is of interest for the rapid and effective transport of both safety and infotainment applications [17]. Geographical dissemination based techniques are surveyed in [18, Ch. 5][19].

The ETSI definitions of the GeoNetworking protocol [16] and network architecture [20] enable the multihop dissemination of messages in the VANET, merging the dissemination functionality into the vehicular networking layer and preserving the underlying MAC and PHY radio protocol layers as they are defined in the IEEE 802.11p. The Contention Based Forwarding (CBF) component of the GeoNetworking protocol (section E.3 of [16]) defines a timer-based dissemination logic for broadcast messages. A node A receiving a message from node B, checks if it has already received and dealt with the received message. In case it is new, A sets a timer according to the value

$$T = \begin{cases} T_{max} - (T_{max} - T_{min})\frac{d_{AB}}{d_{max}} & d_{AB} \le d_{max} \\ T_{min} & d_{AB} > d_{max} \end{cases} \tag{1}$$

where T_{max} and T_{min} are the maximum and minimum values set for the GeoNetworking broadcast message timer; d_{max} is the theoretical maximum communication range of the wireless access technology; d_{AB} is the distance between A and B.

If A receives more copies of the same message while the timer is running and A's copy of the message is scheduled for re-broadcasting, it cancels its scheduled copy and gives up to the re-broadcasting action (*inhibition rule*). If A ends up sending its scheduled copy of the message (i.e., it does not get inhibited because of further received copies of the same message), then A is elected to be a *forwarding node* for that message. The dissemination algorithm suppresses most duplicate messages by electing designated nodes to act as forwarders.

Under our proposed mechanism, the forwarding nodes designated by the dissemination logic are used as a covering set of the vehicles, rather than to actually disseminate data flows. To underline the different purpose of the forwarding nodes in our scheme, we rename them as *representative nodes*. The representative nodes would then be used to send across the LTE network (to the FPS) status messages about themselves and about their neighbors (that they know about through the conduct of a background CAM exchange).

B. Election of representative nodes: connected VANET case

We define a REQUEST message that is originated by a *trigger node*, starting the dissemination-like process. The trigger node can be an RSU located in a central position of the target area, or it can be a specially designated OBU (e.g., the one closest to a centroid position). The REQUEST message is disseminated according to the rules used by the GeoBroadcast protocol concisely stated in Sec. III-A. The nodes that are elected as forwarders of the REQUEST message during this dissemination phase, are identified as *representative nodes*. They are in charge of reporting the status data of their neighboring vehicles to the FPS via LTE connections.

Let A denote a generic node that sends the REQUEST message (hence A is the trigger node or any of the elected representative nodes). The message sent by A contains: i) an identifier; ii) the geographical position of A; iii) a count-down hop count field, initialized by the trigger node to the maximum number of hops H that the REQUEST message is allowed to travel and decremented by each re-broadcasting node; iv) a list of IDs of the vehicle nodes that A commits to report to the FPS on.

By re-broadcasting the REQUEST message, a node A recognises to have been designated to act as a representative node. Hence, the node A constructs a reduced neighbor vehicle database $rLDM$ by omitting from its full LDM those nodes whose IDs are listed in the REQUEST message that A has received. The list of IDs contained in the $rLDM$ is inserted in the copy of the REQUEST message that A sends out. A will report FCD relative to only those vehicles that appear in its $rLDM$. Since a single representative node is elected for each VANET radio neighborhood (the maximum 802.11p vehicular radio transmission range d_{max} being in the order of several hundred meters), the number of LTE channels that are effectively used for the transmission of messages is drastically reduced.

C. Election of representative nodes: multiple connected components case

Let T_{SC} define the time period of one cycle of the SETUP plus COLLECTION phases. The trigger node starts a new time period by issuing a new REQUEST message every T_{SC} seconds. This time period can be broken up into a SETUP phase of duration T_S, when representative nodes are elected, and the ensuing COLLECTION phase, when a new set of FCD is sent by current representative nodes every T_C seconds, until the COLLECTION phase is terminated and a new set of representative nodes is to be elected.

Given the maximum number of hops H that the REQUEST message is allowed to traverse (which is related to the ratio between the radius of the target areas and d_{max}, typically under few tens), the REQUEST message dissemination delay over the connected component of the VANET that the trigger node belongs to assumes a value that lies between HT_{min} and HT_{max}. Practical values of T_{max} are in the order of 100 ms. Then, the maximum message dissemination delay is typically below few seconds.

In general, a nodal vehicle A which is located inside the target area sets a timer value to $T_V = HT_{max}$. If the timer expires and no REQUEST message has been received by A, the nodes declares itself to belong to a system connectivity graph component that is different than the component in which the trigger node is located. Then, the node A considers whether sending a *secondary* REQUEST message and two cases arise: i) the LDM of A is empty, i.e., as far as A knows, it has no neighbours; ii) the LDM of A contains some data.

In the first case, A will send its own FCD to the FPS via a dedicated LTE connection initiated by A itself, since it declares itself to be isolated, so that it cannot be part of the aggregated data sent by another elected representative node.

In the second case, A sets a secondary timer, initialized to a value drawn randomly from the interval $[0, (T_S - 2T_V)/n_A]$, where n_A is the number of neighbors listed in A's LDM database. We assume that $T_S \geq 3T_V$. If no (secondary) REQUEST message has been received by A by the expiration time of the secondary timer, then A issues a secondary REQUEST, i.e., it acts like a substitute trigger node[1]. If instead, A receives a secondary REQUEST before its secondary timer expires, then it deals with it just the same way it would have done with the primary REQUEST, i.e., A applies the dissemination logic to the secondary REQUEST message.

This mechanism manages to define other representative nodes in connected components of the VANET graph to which the trigger nodes is not connected. In case the vehicular density is quite low so that a high fraction of the vehicles are isolated, the above algorithm sets a configuration that establishes individual LTE connections (one for each vehicle).

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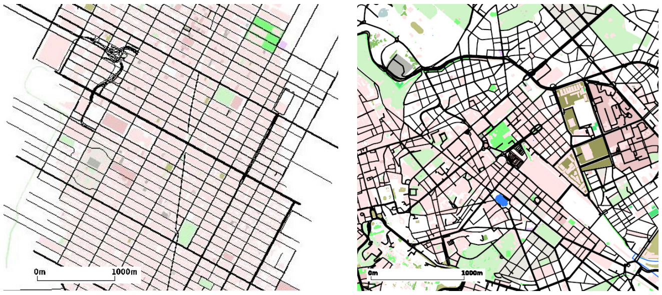
[1] The secondary REQUEST message can contain a flag signalling that it has not been issued by the trigger node.



(a) Manhattan District. (b) Rome.

Fig. 3. Urban scenarios

Under high density conditions, a single connected component exists. In this case, the dissemination of a single REQUEST message that is issued by the trigger node, is sufficient for inducing the election of a set of representative nodes that covers all vehicles in the target area.

IV. SIMULATION MODEL

We evaluate the performance of our proposed mechanisms by using a multi-layer simulation tool that is constructed as a composition of the following simulation modules: SUMO [21], for the vehicular micro-mobility simulation, OMNET++ [22], for the communication network simulator, and Veins [23], a software module that interconnects SUMO and OMNET++, allowing data import and export between the two.

We consider actual urban maps of the city centers of Rome and New York, obtained by OpenStreetMap [24], to define two urban scenarios. The first is the district of Manhattan in the city of New York (see Fig. 3(a)). This map is mainly characterized by a regular grid of avenues and streets that create a considerable number of junctions. The second considered scenario covers the neighborhood of Termini Central Station in the city of Rome (Fig. 3(b)). In contrast with the first scenario, this one is characterized by a high level of road layout irregularity and a higher measure of stochastic street orientations.

Mobility of vehicles is generated by the micro-mobility simulator SUMO, according to the so called ”random trips” model. The movement of the vehicles is governed by the car-following model with a target speed of 50 km/h. According to vehicle density in each road lane, the actual realized velocity can be lower than the target one.

The OMNET++ simulation tool is used to simulate the behavior of the communications process, including the operations of the Physical, MAC and network layers. The MAC and PHY parameters are set equal to those specified by the IEEE 802.11p standard. We have embedded the implementation of the dissemination logic described above in the network layer. We invoke the packet broadcasting operations mode, under which no ACK frames are produced at the MAC layer.

As for the VANET, we have jointly used two attenuation models: the Two Exponents Model (TEM) [25] and the Simple Obstacle Shadowing Model (SOSM) [26]. The TEM models the distance dependent component of the power loss: it assumes that the attenuation is $A(d) = \kappa d^{\alpha_1}$, for distances d up to a break point value d_{bp}. For $d > d_{bp}$, it is $A(d) = \kappa d_{bp}^{\alpha_1 - \alpha_2} d^{\alpha_2}$. Typical values of the path loss parameters are $d_{bp} = 120\ m$, $\alpha_1 = 2$, and $\alpha_2 = 4$. The SOSM reproduces in Veins the shadowing effect of a real urban environment: it describes the attenuation as a function of the depth of the buildings crossed by radio links.

We assume that an RSU is located at the most central intersection of each considered map. The RSU is set to assume the role of the trigger node. The LTE eNodeBs are located according to a regular square grid of side length R_{eNodeB}, with one LTE station co-located with the RSU (Fig. 1). The COST-Hata model of path loss for urban areas has been used to evaluate the vehicle node Channel Quality Indicator (CQI) and the LTE cell that each vehicle node is associated to (the one with the best detected CQI). The Modulation and Coding Set (MCS) is set by each vehicle node transmitting over an LTE channel according to its observed CQI, unless stated otherwise.

Numerical values used for simulation parameters are listed in Tab. I. Every considered scenario, over a zonal scope of about 12 km^2, has been analyzed under three different vehicular densities λ, as reported in Tab. I.

TABLE I
NOTATIONS AND SIMULATION PARAMETER VALUES

Parameters	**Values**
$\lambda_{Manhattan}(vehic/km^2)$	$70, 96, 110$
$\lambda_{Rome}(vehic/km^2)$	$70, 80, 87$
Vehicle target speed (km/h)	50
R_{eNodeB} (m)	$500 \div 3500$
d_{max} (LOS) (m)	827
T_{min} (ms)	0
T_{max} (ms)	100
Hop limit H	20
Propagation Model for IEEE 802.11p	TEM + SOSM
VANET MAC, PHY parameters	IEEE 802.11p
IEEE 802.11p Link Rate (Mbit/s)	6
IEEE 802.11p tx power (dBm)	27
Carrier frequency 802.11p (GHz)	5.9
LTE UE tx power (dBm)	27
Carrier frequency LTE (GHz)	0.8

The baseline solution that we compare our approach with, denoted as LTE in the graphs, sets a configuration under which each vehicle sends its own CAM directly to the eNodeB using the LTE access network. This solution represents the performance obtained when vehicular data are gathered by using only the LTE network [5][6][7]. Also, it represents the performance behavior of the Hybrid LTE-VANET mechanism during the SETUP phase [10][11][12][13].

V. PERFORMANCE ANALYSIS

A. Performance metrics

We employ the following performance metrics:

f_{RV}	fraction of all vehicles roaming in the target area that are reached by the REQUEST message propagated according to the dissemination logic in the VANET;
f_{RN}	fraction of all vehicles roaming in the target area that are elected as representative nodes (vehicles that forward the REQUEST message) in the VANET;

TABLE II
PERFORMANCE METRICS FOR THE DISSEMINATION OF THE REQUEST MESSAGE IN THE NEW YORK (NY) AND ROME (RM) SCENARIOS.

	λ (veh/km^2)	f_{RV}	f_{RN}	f_{MV}	D_{RQ} (s)
NY map	70	0.96	0.25	0.97	0.29
	96	0.97	0.20	0.97	0.27
	110	0.98	0.19	0.98	0.27
RM map	70	0.90	0.26	0.96	0.48
	80	0.93	0.23	0.96	0.50
	87	0.92	0.21	0.97	0.56

f_{MV} fraction of all vehicles roaming in the target area whose data are reported to the FPS via LTE connections established by the representative nodes;

L_{data} the average amount of data sent by a representative node over its LTE PUSCH during the SETUP phase;

D_{RQ} dissemination delay: time needed to complete the dissemination-based propagation of the REQUEST message, measured from the instant that this REQUEST message is issued by the trigger node to the time that it has completed its dissemination over the graph component to which the trigger node belongs;

M_{CH} number of LTE Physical Uplink Service Channels (PUSCHs) [27] that must be established over a cell for use in gathering data;

M_{RB} total number of LTE Resource Blocks (RBs) [27] required by vehicles for communicating over the LTE system.

The performance analysis that we carry out accounts for the conduct of the two operations: dissemination of the REQUEST message over the VANET system and vehicle data reporting by the elected representative nodes through the LTE system.

B. Dissemination of the REQUEST message

Performance behavior is assessed by means of evaluation of the metrics f_{RV}, f_{RN}, f_{MV} and D_{RQ} in the two urban scenarios described in Sec. IV. Results are presented in Tab. II.

In the NY map, f_{RV} is almost insensitive to the vehicular density level and it is close to 1 ($f_{RV} \simeq 0.97$). As for f_{RN}, we note that the observed values range between $f_{RN} \simeq 0.25$ for $\lambda = 70\, veh/km^2$ down to $f_{RN} \simeq 0.19$ for $\lambda = 110\, veh/km^2$. The fraction of vehicles that serve as representative nodes is thus noted to reduce as the vehicular density is higher, i.e., the efficiency of the aggregation operated by the representative nodes improves with growing levels of λ.

As for the Rome map, f_{RV} is again quite stable with different vehicle density levels, although it settles to slightly lower values than with the NY map ($f_{RV} \simeq 0.93$ for Rome). Also in this case f_{RN} decreases with the vehicle density, consistently taking higher values than in the NY case.

In both NY and Rome cases, the fraction of monitored vehicles f_{MV} is close to 1 and insensitive to the vehicle density level. In other words, the designated representative nodes do actually represent (cover) essentially all vehicles roaming in the target area.

The dissemination time D_{RQ} is somewhat dependent on the vehicular density level λ. In the NY scenario, for the lowest λ, it took approximately 290 ms for the message to reach 97% of the vehicles. The message dissemination delay decreases to 267 ms for the highest tested λ. The corresponding values for the Rome scenario range are between 480 ms and 560 ms.

The higher levels of delay and f_{RN} observed in the Rome map are due to the irregularity of the street layout that is noted to have lower vehicular communications connectivity, so that a larger number of hops are needed to reach out distant vehicles.

C. Load on LTE cellular system

Once the representative nodes are elected, they proceed to report the FCD of the vehicles roaming in the region of interest. We investigate the case where the reported FCD data contains the vehicles' geographical positions. Under our approach, each representative node sends a REPORT message with its own FCD and the positions of the vehicles whose IDs are listed in the $rLDM$ built during the REQUEST dissemination phase (see Sec. III-B). The REPORT message sent by each representative node consists of:

- network plus transport headers (IPv6+UDP) of 48 bytes (see Table 1 in [5]);
- an application level header of 48 bytes, that contains the representative node ID, its position and the same data as envisaged in the Vehicle High Frequency Container of the CAMs[2]; moreover, it contains also the number $n \geq 0$ of ensuing records, relevant to neighbor vehicles' data;
- a list of records: each record has a length of 32 bytes, and it is made up of: i) a 1 byte sequence number; ii) a 17 byte encoding of the 17 characters US NHTSA standard Vehicle Identification Number; iii) the position of the reported vehicle, encoded with 14 bytes.

Overall, a REPORT message containing data from n neighborhood vehicles has a length of $96 + 32n$ bytes. The size values of L_{data} for NY (Rome) range between 1.231 kbit and 0.978 kbit (1.018 kbit and 0.892 kbit) for the lowest and highest vehicle density level, respectively. It is apparent that the average amount of data that each representative node has to transfer over the LTE connection is quite limited.

We investigate the performance behavior of the urban scenarios by varying the value of the LTE eNodeB distance R_{eNodeB} and by considering different vehicular densities. The crucial points are: i) the overhead implied by setting up and maintaining an active LTE connection, hence the number of used LTE channels per cell; ii) the load seen by an LTE eNodeB due to the overall number of vehicle nodes under its coverage that require an LTE connection.

The impact of the vehicle data transfer through the LTE access network is highlighted by the results in Fig. 4. The metrics M_{CH} and M_{RB} are plotted as a function of the inter-eNodeB distance, R_{eNodeB}, for the NY map (Fig. 4(a)) and

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[2] Our setting is consistent with [5], where it is mentioned that the maximum length of a CAM containing only the mandatory fields, including the Basic Container and the Vehicle HF Container, is 50 bytes.

the Rome map (Fig. 4(b)). In these figures, we compare two approaches: i) each vehicle sends its own data individually, by using its own dedicated LTE connection (curves labelled with LTE[3]); ii) the proposed protocol is used, representative nodes are elected and only those nodes report data about themselves and about their respective neighbors via their LTE connections, as described in Sec. III-B (curves labelled with $VANET$).

As for M_{CH}, under the LTE approach (curves with the square marker), each eNodeB uses a number of radio channels that is equal to the total number of vehicles included in the coverage area. This grows quickly as the area covered by a single eNodeB expands. In comparison with the LTE approach, we note the $VANET$ scheme (curves with circle markers) to exhibit the following features: it is able to reduce the number of nodes elected to report vehicles' data via the LTE access network, approaching the much reduced M_{CH} performance levels, leading to reduction of the data rates across each LTE channel.

The last point is highlighted by the performance curves for M_{RB}, the average number of RBs used per LTE cell. We identify two performance bounds: i) the best case, when each node using an LTE channel is able to use the high rate MCS, namely 64 QAM with code rate 2/3; ii) the worst case, when every node using an LTE channel must use of lower rate MCS, namely QPSK with code rate 1/2. Besides those bounds, we also evaluate the intermediate case, where each node using an LTE channel measures its CQI and infers what is the best MCS that it can use (curves labelled with *adapt*).

In Fig. 4, we show that the $VANET$ approach can drastically reduce the number of RBs occupied, in comparison with the LTE approach, given the use of a prescribed modulation/coding scheme. In particular, the worst performance exhibited under the $VANET$ approach is close to the best performance obtained under the LTE scheme for the highest λ. The performance gap between the corresponding bounds and between the two approaches (e.g., as measured by the adaptive case) broadens as the number of eNodeBs is reduced. This is a critical issue, since low intensity data collection of FCD should be taken care of by macro-cells, rather than by hot spot micro-cells, intended to boost the capacity offered in special areas for broadband users. On the other hand, macro-cells cover urban areas that can encompass hundreds of vehicles. Hence, the $VANET$ scheme proposed herein is highly effective in supporting massive FCD collection.

Another performance advantage offered by the proposed approach is appreciated by examining the results shown in Fig. 5. The metric M_{RB} is plotted vs. R_{eNodeB} for three different vehicular density levels, in the NY and Rome scenarios. We compare the adaptive LTE channel performance obtained under the $VANET$ and LTE approaches under two alternative cases: i) only vehicular positions are reported to the FPS via LTE (the same case as the one shown in Fig. 4); ii) both vehicular positions *and* VANET connectivity information is reported to the FPS. The latter case is appealing for a centralized optimization of inter-vehicular communications, e.g., for content distribution; in general, whenever the knowledge of the VANET topology can be exploited profitably.

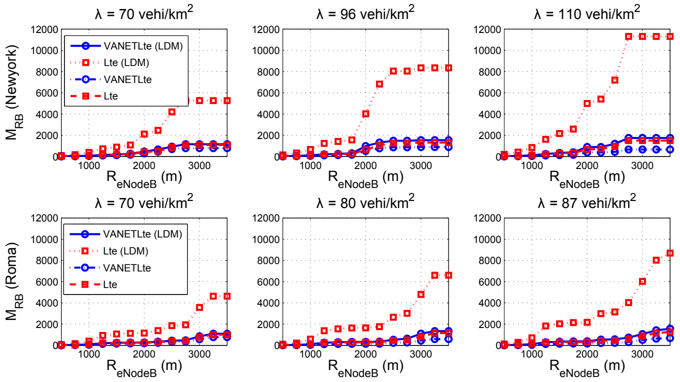

Fig. 5. Average number of RBs per cell, M_{RB}, used by nodes transmitting over the LTE channels vs. R_{eNodeB} for three density levels, NY map (top three graphs) and Rome map (bottom three graphs). The red curves (square markers) refer to the case where full connectivity information is transferred, in addition to node positions. The blue curves (circle markers) correspond to the case where only nodal position information is transferred.

It is noted that the advantage of our approach is enhanced when it is required to transfer information that includes nodal positions as well as their connectivity relationships within the VANET. In fact, under our $VANET$ approach, this amounts to transferring the full list of neighboring nodal IDs and positions, rather than only those listed in the reduced table $rLDM$. Hence, the difference is impacted by the number of common neighbors of adjacent representative nodes. Under the LTE framework, each vehicular node reports information about itself only, involving only its position, or the full list of its neighbor positions in addition to its own one.

VI. CONCLUSIONS

In this paper, we present and study methods used to support the communications transport of Floating Car Data message flows in a hybrid LTE-VANET architecture. Under our proposed new scheme, we employ a basic VANET network layer protocol for disseminating messages across the VANET, and use it to elect vehicles that will act as cluster heads. The latter connect to the LTE system to report the positions of (and possibly other information for) vehicles that travel the target area. Such a scheme leads to significant reduction in the LTE channel capacity required for such data transport, when compared with the capacity required by using the techniques proposed to date. Under the latter, the collection of FCD is accomplished by having each individual vehicle connect through its own established channel across the LTE radio access network (RAN), whereby the established channel can be used during the full process or only during a SETUP period. We exhibit the LTE channel load relief offered by our scheme by evaluating two illustrative urban scenarios. We consider medium to high vehicular density levels. Our results well confirm the significant performance gain, as expressed in terms

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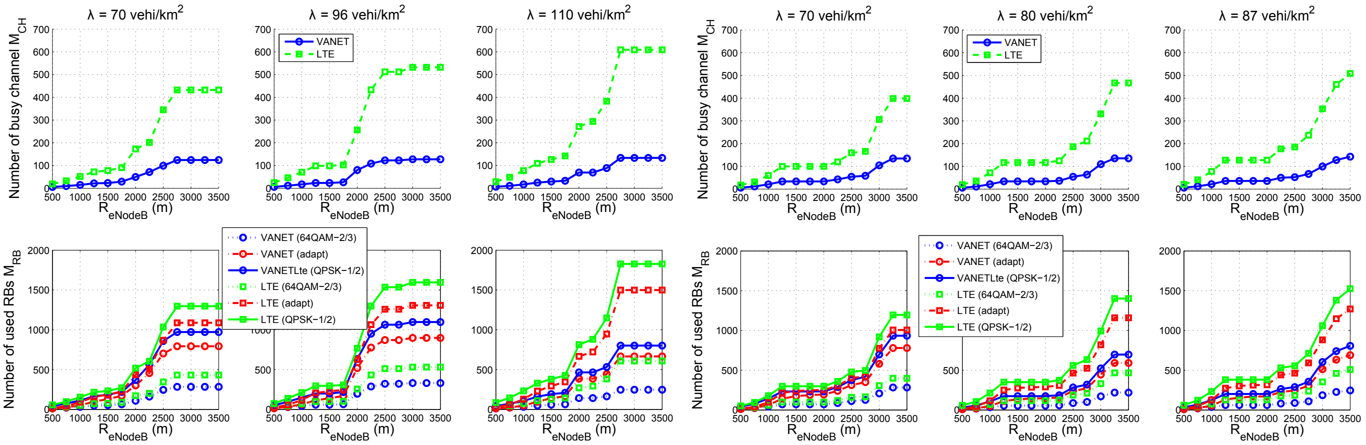
[3] This case corresponds only to the SETUP phase in case a Hybrid VANET-LTE scheme is used, as defined in Sec. II-A.



(a) New York

(b) Rome

Fig. 4. Average number of LTE uplink radio channels used per cell, M_{CH}, (top graphs) and average number of uplink RBs used per cell, M_{RB}, (bottom graphs) vs. the eNodeB transmission range R_{eNodeB} for three different vehicular density levels.

of the saved number of LTE RBs, that can be of an order of magnitude in case the nodes reported FCD include complete information on VANET connectivity.

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