The Dynamics of Vehicular Networks in Urban Environments

Nicholas Loulloudes George Pallis Marios D. Dikaiakos

Department of Computer Science, University of Cyprus

Abstract

Vehicular Ad hoc NETworks (VANETs) have emerged as a platform to support intelligent inter-vehicle communication and improve traffic safety and performance. The road-constrained, high mobility of vehicles, their unbounded power source, and the emergence of roadside wireless infrastructures make VANETs a challenging research topic. A key to the development of protocols for inter-vehicle communication and services lies in the knowledge of the topological characteristics of the VANET communication graph. This paper explores the dynamics of VANETs in urban environments and investigates the impact of these findings in the design of VANET routing protocols. Using both real and realistic mobility traces, we study the networking shape of VANETs under different transmission and market penetration ranges. Given that a number of RSUs have to be deployed for disseminating information to vehicles in an urban area, we also study their impact on vehicular connectivity. Through extensive simulations we investigate the performance of VANET routing protocols by exploiting the knowledge of VANET graphs analysis.

I. Introduction

Inter-vehicle communication (IVC) has emerged as a promising field of research and development, where advances in wireless and mobile ad-hoc networks, global positioning systems and sensor technologies can be collectively applied to vehicles and result to great market potential. The idea of employing wireless communications in vehicles dates back to the ’80s, but recently the resolution of governments and national traffic administrations to allocate wireless spectrum for vehicular communications, along with the adoption of standards like the Dedicated Short Range Communications (DSRC), has provided a real
thrust in the field of IVC or Vehicular Ad-Hoc Networks (VANETs). VANETs comprise vehicle-to-vehicle and vehicle-to-infrastructure communications based on wireless local area network technologies. Unlike cellular communication networks, VANETs do not necessarily need continuous coverage, rather, they can be supported by hot spots in correspondence of roadside infrastructure units (RSUs), which aim to gap intermittent connectivity among vehicles.

The development of VANETs and their use in the deployment of vehicular applications and services has been the target of research investigations in the recent literature, as well as of industrial projects run by large government-sponsored consortia (Vehicle Safety Consortium - USA, Car-2-Car Communication Consortium and CVIS - EU), along with field trials (Vehicle Infrastructure Integration, USA) [1], [2], [3].

Due to the nature of vehicular mobility, VANETs are characterized by highly dynamic topologies and are frequently prone to network disconnection and fragmentation. Consequently, these inherent characteristics are bound to degrade the quality of services provided by the VANET infrastructures. Therefore, the establishment of robust VANETs that could effectively support multi-hop communications and applications on a large geographical scale remains an open challenge.

A. Motivation

The motivation of this work stems from the fact that the study of the structural properties of large, real-world, dynamic graphs (such as the Internet topology, Web and e-mail graphs, collaboration, biological and on-line social networks) has lead to crucial observations having significant influence in computer science. For instance, the discovery of power laws in the Internet topology by M. Faloutsos, P. Faloutsos and C. Faloutsos in [4], brought a revolution to the field, since it enabled the design and the performance analysis of information routing protocols. Therefore, the study of the networking shape of VANETs is of paramount importance, currently gaining considerable research attention, momentum, and expected to be of increasing interest to the networking community in general. With a better understanding of network topology characteristics, the network researchers are able to design network protocols which exploit the

1Although the terms IVC and VANET are not identical, in this work we use the latter in order to emphasize the ad hoc nature of these wireless networks.
unique characteristics of VANETs.

Essentially, a vehicular network is a very challenging and dynamic environment since it combines a fixed infrastructure (RSUs, e.g., proxies), and ad hoc communications among vehicles. Despite the fact that it presents similarities with the traditional Mobile Ad Hoc NETworks (MANETs), the mobile nodes in a VANET (i.e. vehicles) are not energy-starving, are highly mobile, and their mobility is constrained by the underlying road network topology. Moreover, the existence of roadside infrastructure creates opportunities for optimized communications such as data sharing and increased throughput while downloading content on the move. Finally, the connectivity of VANETs is influenced by the market penetration of communication equipment [5]. Apart from the networking aspects, the applications which are expected to run over a VANET make it also a unique environment: safety applications (accident avoidance near intersections, speed “regulation” for road congestion avoidance), peer-to-peer music sharing, Internet access, they all pose interesting questions related to protocol design and network deployment. The challenges featured by VANETs are more related to the ones typically found in DTN (Delay Tolerant Networks) than in infrastructure-based wireless networks.

During the process of designing and deploying a VANET, various questions must be answered that pertain to protocol performance and usefulness. For instance, when performing message routing, a key question is “which are the highest-quality nodes (vehicles)” to be trusted with the forwarding process; when performing multi-hop geocasting, the question is how can we spread the emergency messages with the minimal number of rebroadcasts so as to reduce latency and packet collisions?; when performing periodic single-hop broadcasting, how can we increase the average packet delivery?; when provisioning for the placement of RSUs [7], in order to reduce the average path length between the vehicles and the access points, what is the best deployment strategy that maximizes the dissemination of information?; when designing mobility models [8], which is the distribution of “synapses” per node, i.e., whether there are any clusters (communities)?; furthermore, when the network is disconnected, a significant question concerns the identification of bridge nodes [9] which can ultimately be en-charged with the ferrying of messages.
All these questions and many more require knowledge of the topological characteristics of the VANET communication graph, where vehicles correspond to vertices and communication links to edges. Specifically, vehicular mobility affects the evolution of VANET connectivity over space and time in such a way that critically determines the performance of networking protocols. Therefore, a key question in vehicular networking is: “which effects does mobility generate on the vehicular topology and how can we exploit them in order to improve vehicular communication protocols, especially for “killer applications”, like large data files transfer and real-time information dissemination [10]?”.

B. Paper’s Contributions

The objective of this work is twofold: a) to provide a “higher order” knowledge of the time-evolving topological characteristics of the VANET communication graph, as compared to the “first-order” knowledge provided by the studies reported in [11], [12], [13], [14] and b) to investigate how to use this knowledge towards improving the performance of VANET routing protocols. The present work continues and improves upon the authors’ preliminary efforts in [11] towards deriving insightful implications for the vehicular networking community. Using both real and realistic vehicular mobility traces, as well as current and future wireless communication technologies, in a range of real-world urban environments, we study the structure and evolution of the communication graphs under different market penetration ratios of VANET-enabled vehicles. Also, we study the impact of the presence of stationary RSUs has on the VANET connectivity, since such an infrastructure has a potentially significant effect on inter-vehicle connectivity in urban environments. Our research goes one step further and we examine the impact of our findings in the design of VANET routing protocols. Through extensive simulations, we explore how the knowledge of the networking shape of vehicular network could enhance the design of routing protocols. To the best of our knowledge, this is the first attempt to study the network connectivity of urban traffic as well as its impact in the design of VANET routing protocols in such a systematic and comprehensive way. The main contributions of this work can be summarized as follows:

- Data Knowledge Perspective: A thorough study of the visible and “latent” structure of the vehicular network, including metrics used in earlier studies [12], [11], [13], as well as several other metrics
traditionally used in the field of social network analysis, i.e., community analysis. Using both real and realistic mobility traces, we study the networking shape of VANETs in urban environments under different transmission and market penetration ranges. Given that a number of RSUs have to be deployed for disseminating information to vehicles in an urban area, we also study their impact on vehicular connectivity.

- **Engineering Perspective:** Based on the analysis conducted, we examine the implications of our findings in the design of two indicative VANET routing protocols (VADD [15], GPCR [16]). Through extensive simulations, we investigate how the performance of routing protocols can be improved using the knowledge of VANET graph analysis. We provide significant perspectives and insights into how vehicular protocols should be designed for urban traffic.

The rest of the paper is organized as follows: Section II briefly surveys the relevant work; Section III describes the metrics used in the present study to characterize the evolution of VANET communication graph; Section IV provides detailed information concerning the source of the data studied here. Section V records the findings of the study. Section VI examines whether the findings from the VANET graph analysis can be utilized by two known VANET protocols (VADD and GPCR) during their routing decision processes. Finally, Section VII concludes the article.

II. RELEVANT WORK

Our work draws inspiration from the rich body of prior work on frameworks for studying the temporal evolution of several real graphs [17]. These graphs arise in a wide range of domains (i.e. autonomous systems, e-mail networks, citations) and their study leads to significant implications since most of real-world dynamic networks (online social networks, Internet etc.) have been proved to follow some topological statistical features (i.e. features of scale-free networks, small-world properties, power-law degree distribution etc.).

In this work, we focus on exploring the time-evolving VANET graphs where the mobility of nodes affects the evolution of network connectivity over space and time in a unique way. Inter-vehicle communication (IVC) has emerged as a promising field of research [18], [19], [20], where advances in wireless
and mobile ad-hoc networks can be applied to real-life problems (traffic jams [21], [22], [23], road accidents [24], [25] etc) and lead to a great market potential [26], [2]. Connectivity dynamics, in turn, determine the performance of networking protocols, when they are employed in vehicle-based, large-scale communication systems. The value of the connectivity analysis of ad hoc networks is so fundamental that recently a competition-experiment has been started — the MANIAC experiment [13]— to study network connectivity, diameter, node degree distribution, clustering, frequency of topology changes, route length distribution, route asymmetry, frequency of route changes, and packet delivery ratio. The obtained results show a high degree of topology and route changes, even when mobility is low, and a prevalence of asymmetric routes, both of which contradict assumptions commonly made in MANET simulation studies. Regarding link duration statistics, authors in [27] used simulations to study the probability densities of link lifetime and route lifetime for some mobility models. According to this study, the path duration seems to be a good metric in order to predict the general trends in the performance of vehicular routing protocols. Another sound observation is that they showed the relationship between the path duration and other critical parameters such as the transmission range and the average relative speed of the mobile nodes, and the average number of hops in the path. Also, well-known concepts from social network analysis have been used as primitives to design advanced protocols for routing and caching in DTNs and ad hoc sensor networks. In [9], the betweenness centrality index and its combination with a similarity metric (comprising both the SimBet metric) have been used to select forwarding nodes to support information routing in DTNs. Results showed that data dissemination is improved if the messages are delivered through nodes which have high SimBet utility values. The betweenness centrality has also been used in [28] to design a cooperative caching protocol for wireless multimedia sensor networks. This protocol selects the mediator nodes that coordinate the caching decisions based on their “significant” position in the network. Likewise, the MaxProp protocol [29] transfers messages based on the mobility of intermediate nodes. In a related study [30], the authors combine short-range communication and cellular communication to facilitate query processing in VANETs. Yoneki studied the impact of connective information (clustering, network transitivity, and strong community structure) on epidemic routing in a series of works [31].
In the context of vehicular networking, authors of [32] present a preliminary characterization of the connectivity of a VANET operating in an urban environment. They transform the vehicular network into a transitive closure graph. Then, the temporal evolution of the average node degree is presented. Nonetheless, the authors do not perform a deep analysis of the networking shape of vehicular mobility and limit their study only to the average node degree for a small time interval. In [33], the authors set up a real-world experiment consisting of 10 vehicles making loops in a 5-mile segment of a freeway. They focus on the connectivity issues without investigating the topological properties of the VANET graph. Authors in [12] study the node degree distribution, link duration, clustering coefficient and number of clusters for VANET graphs under various vehicular mobility models. The objective of [12] focuses on studying the topological properties of different mobility models and explaining why different models lead to dissimilar network protocol performance. The authors of [34] provide an analysis of the connectivity of vehicular networks by leveraging on well-known results of percolation theory. Using a simulation model, they study the influence of vehicle density, the proportion of equipped vehicles, transmission range, traffic lights and roadside units. Similarly, authors in [35] study the distributions of node degree and link duration in VANETs using a realistic urban traffic simulator. In a recent study [36], authors study the vehicular network in order to develop a stochastic traffic model for VANETs. This model captures spatial and temporal characteristics of a vehicular network, vehicle movement, link condition, and node connectivity. There has also been a recent work in [14] which is closely related to ours. Specifically, the authors present a comprehensive analytical framework, as well as a simulation framework, for network connectivity of urban VANETs, using some key system parameters such as link duration, connection duration, and rehealing time. The analytical framework leads to closed-form expressions which capture the impact of four critical parameters (network density, transmission range, traffic light mechanisms, and size of a road block) on network connectivity. Unlike our work, the authors do not study how the observations derived from the study of the structure of the vehicular network affects well known vehicular communication protocols (e.g., VADD [15], GPCR [16]). In addition, we study the impact of roadside units in the networking shape of VANET graphs.
In [11], we studied the structure and evolution of a VANET communication graph using realistic traces from the city of Zurich. However, the traces utilized in [11] are characterized by highly variable vehicular densities. In this work, we extend the analysis of VANET graphs from the previous studies in [12], [34], [14] by introducing additional new measurements and new data sets. Considering that the usefulness of the findings of this research study depends on the realism and completeness of the data upon which the study is based, we use both real and realistic vehicular traces. Another extension of this work is that we examine the implications of our findings in the design of two indicative VANET routing protocols. Through extensive simulations, we study how the knowledge of the networking shape of vehicular network can be beneficial.

III. GRAPH METRICS EXAMINED

This section contains the definitions of the metrics used in the study. We categorize the examined metrics as network-oriented, centrality, link duration and cluster-oriented. All node IDs mentioned in this section refer to the sample graph of Figure 1. For the sequel, we will consider $G(t)$ to be an undirected graph of VANET at time $t$, where vehicles correspond to the set of vertices $V(t) = \{u_i\}$ and communication links to the set of edges $E(t) = \{e_{ij}\}$. An edge $e_{ij}(t)$ exists, if $u_i$ can communicate directly with $u_j$ at time $t$, with $i \neq j$.

A. Network-oriented metrics

Network-oriented metrics depict the shape of VANETs, capturing and quantifying the richness of network connectivity. These metrics reflect the topological properties of a vehicular network, stimulating interesting considerations on how network protocols could take advantage of vehicular mobility to improve their performance.

- **Node degree.** The number of vehicles within the transmission range of a node. Formally, the degree of $u_i$ at time $t$ is defined as $D_i(t) = \| \{ u_j \mid \exists e_{ij}(t) \} \|$.

- **Effective Diameter.** The minimum distance in which the 90th percentile of all connected pairs of vehicles can communicate with each other. It is a smoothed form of network diameter which we use
for our studies.

- **Density.** Defined as the ratio between the number of edges in the $G(t)$ and the maximum number of edges possible for $G(t)$.

![Fig. 1: Snapshot of a sample VANET graph.](image-url)

### B. Centrality metrics

Centrality metrics have been developed in social network analysis to quantify how important particular individuals are in social networks. The objective is to find people who are central to communication and important for information dissemination. Centrality metrics are designed such that the highest value indicates the most central node. In [11], we observed several centrality metrics and concluded that for VANETs, Betweenness Centrality and the Lobby index provide a good measure as they relate to the expected role a node plays within the vehicular ad hoc network.

- **Betweenness Centrality** [37]. Defined as the fraction of the shortest paths between any pair of nodes that pass through a node. The betweenness centrality of a vehicle $u_i$ at time $t$ is:

$$BC_i(t) = \sum_{j \neq k} \frac{sp_{j,k}(u_i,t)}{sp_{jk}(t)}$$

where $sp_{j,k}$ is the number of shortest paths linking vertices $j$ and $k$ at time $t$ and $sp_{j,k}(u_i,t)$ is the number of shortest paths linking vertices $j$ and $k$ that pass through $u_i$ at time $t$. Betweenness centrality is a measure of the extent to which a vehicle has control over information flowing between others (e.g., $BC_{14} = 0.668$).

- **Lobby Index** [38]. The lobby index of a given vehicle $u_i$ at time $t$, denoted as $L_i(t)$, is the largest integer $k$ such that the number of one-hop neighbors of $u_i$ in graph $G(t)$ with degree at least $k$ equals $k$. This metric can be seen as a generalization of $D_i(t)$, conveying information about the neighbors of the node as well (e.g., node with ID 8 has lobby index 2).
C. Link level metrics

The metrics of this category reflect the network connectivity over a period of time. These metrics are critical both for the periodic single-hop broadcast primitive, where a vehicle broadcasts its current information (location, velocity) in its direct neighborhood, and also for the multi-hop geocast primitive, where several data exchanges between vehicles take place during one communication session.

- **Number of connected periods.** The number of established links between a pair of vehicles within a given time period. A connected period is the continuous time interval during which a physical link is established between two vehicles as a consequence of one being in the transmission range of the other.

- **Link duration.** The time duration of a connected period. Formally, the duration $l_{ij}(t)$ of the link from $u_i$ to $u_j$ at time $t$ is defined as $l_{ij}(t) = t_c - t_o$, if $\exists e_{ij}(t)$, where $t \in [t_o, t_c]$ and $\not\exists e_{ij}(t')$, where $t' < t_o$ or $t' > t_c$.

- **Re-healing time.** The time span between two successive connected periods of a pair of vehicles. Formally, the duration $r_{ij}(t)$ of the link from $u_i$ to $u_j$ at time $t$ is defined as $r_{ij}(t) = t_m - t_k$, if $\exists e_{ij}(t)$, where $t \in [t_a, t_k]$ and $\exists e_{ij}(t)$, where $t \in [t_m, t_z]$ and $t_a < t_k < t_m < t_z$.

D. Cluster metrics

The examined cluster metrics present the dynamic properties of clusters and dense subgraphs established inside a VANET communication graph. The existence of vehicle communities is important in terms of information propagation, since they can act as “data islands” in a vehicular environment.

- **Number of Clusters.** The number of co-existing, non-connected clusters of nodes at a given instant. We define as cluster a connected group of vehicles. A connected group is a sub-graph of the network such that there is a path between any pair of nodes.

- **Clustering Coefficient.** It measures the cliquishness of a network. The clustering coefficient $p_k(t)$ of a cluster $k$ at time $t$ (as defined in [12]) is:

$$p_k(t) = \frac{2|E_k(t)|}{|N^k(t)||N^k(t)| - 1},$$ (2)
where $|E_k(t)|$ is the number of existing links in cluster $k$ at time $t$ and $|N^k(t)|$ is the number of nodes in cluster $k$ at time $t$. The clustering coefficient has a maximum value 1 if the cluster is a clique.

- **Number of Communities [39]**. The number of existing communities at a given instant. A community is defined as a dense sub-graph where the number of intra-community edges is larger than the number of inter-community edges. In order to identify communities, we transform $G(t)$ to directed graph so as $D_{U_i}^{in}(t) = D_{U_i}^{out}(t) = D_{U_i}(t)$, where $D_{U_i}^{in}(t), D_{U_i}^{out}(t)$ is the in-degree and out-degree of node $u_i$ at time $t$. Formally, a sub-graph $U(t)$ of a VANET graph $G(t)$ at time $t$ constitutes a community, if it satisfies:

$$
\sum_{u_i \in U} (D_{U_i}^{in}(t))(U(t)) > \sum_{u_i \in U} (D_{U_i}^{out}(t))(U(t)),
$$

i.e., the sum of all degrees within the community $U(t)$ is larger than the sum of all degrees toward the rest of graph the $G(t)$.

- **Community Modularity [39]**. Community modularity quantifies in the range of -1 to 1 the division of the graph into communities. Good divisions, which have high modularity values, give communities with dense internal connections and weak connections between different communities. The community modularity $Q$ of a network at time $t$ is:

$$
Q_t = \frac{1}{2m} \sum_{U_i, U_j} [A_{ij} - \frac{D_{U_i}D_{U_j}}{2m}]\delta(U_i, U_j)
$$

where $A_{ij}$ is an element of the adjacency matrix of the network, $m$ number of links and $D_{U_i}$ the degree of node $i$.

**IV. TRAFFIC DATA STUDIED**

This section provides an in-depth overview of the dataset utilized in the study of the VANET communication graph.
A. Vehicular Mobility Traces

The structure and evolution of the VANET communication graph is dictated by vehicles mobility patterns. Hence the utilization of both real and realistic mobility traces in this study was of outmost importance. Except of real traces, we also study traces derived from mobility models which are proven to be realistic. For both real and realistic vehicular traces, we consider real-world urban environments.

1) Real Traces: Real mobility traces were obtained through the Smart City Research Group, [40]. SCRG maintains a dataset of real GPS traces collected from taxis traveling throughout Shanghai, China, in a 24-hour time period. We developed a tool in order to parse the taxi traces and converted them from GPS cylindrical coordinates to Cartesian plane coordinates for better manipulation. A $2Km \times 2Km$ rectangular region around Shanghai city-center was isolated, and the mobility traces of all the taxis that run within this region for a 2-hour time period, were utilized. This clipping process resulted in obtaining the mobility traces of 704 distinct vehicles for our study. According to the authors’ knowledge, the SCRG data set is the largest, publicly available dataset for vehicular traces.

2) Realistic Traces: Due to the size constraints of real traces, we enhance our evaluation by studying realistic mobility traces in real urban road topologies. We employ vehicular traces that follow a steady state behavior, where the number of vehicles in a given region remains constant over time. To this end, realistic mobility traces were generated using the VanetMobiSim [41] vehicular mobility generator. By employing known traffic generation models, VanetMobiSim outputs detailed mobility traces over real-world, accurate, city maps available in the Topological Integrated Geographic Encoding and Referencing (TIGER) database [42] from U.S. Census Bureau. The realism of the mobility models utilized in VanetMobiSim has been validated extensively in [41] using benchmark tests from vehicular traffic flow theory which are highly accepted by the transportation community.

In particular, we chose to generate vehicular traffic within a $2Km \times 2Km$ area bounding the city center of Los Angeles, CA. In the generated scenario all vehicles were set to follow the Intelligent Driver Model with Lane Changes (IDM-LC). More specifically, IDM-LC falls into the car-following mobility models category since individual vehicle behaviour depends on the behaviour of the preceding vehicle. It extends
the basic IDM model, in the sense that it adds intersection handling capabilities to the behaviour of vehicles and the possibility that vehicles change lanes and overtake other preceding vehicles. By examining the respective TIGER map, VanetMobiSim was set to synchronize the operation of traffic signals of 110 different intersections.

To achieve an even higher level of realism in the vehicular traffic generated, we opted to define the average vehicle density (and hence the total number of vehicles) for the area under study, by examining the 2010 Annual Average Daily Traffic (AADT) statistics, which are publicly available through California’s Department of Transportation Traffic Data Branch [43]. AADT measures the total volume of vehicle traffic on a given road for a year divided by 365 days. In general, AADT is obtained through traffic counting using electronic equipment installed on the roadside. Our study on a large number of roads in the area of interest, indicated an average density of $10 \text{ veh/lane/Km}$ during normal driving conditions (not peak hours). With approximately 700 Km of road length (one-way and number of lanes for each individual roads included), VanetMobiSim was set to generate vehicular traffic for a 2 hour period, constantly maintaining 7000 vehicles in the area of interest.

### B. Wireless Communication Technologies

Another key factor that undoubtedly determines the structure and evolution of the VANET communication graph is the technology through which vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) wireless communication is achieved. Currently, the de-facto wireless communication protocol used in research works (simulation, as well as field studies) in the VANET literature is the normal IEEE 802.11a WiFi. However, since this protocol has not been designed having mobility in mind, an amendment to the IEEE 802.11 standard has been proposed to add wireless access in vehicular environments (WAVE). This amendment, designated as IEEE 802.11p, defines the necessary enhancements to support data exchange between high-speed vehicles and between vehicles and roadside infrastructure.

The IEEE 802.11p protocol is still under development and only limited trial implementations exist. To the best of our knowledge, the only available field measurements for the IEEE 802.11p are the
communication performance results in \[44\] from the CVIS project\[3\]. These results indicate that, irrespective of vehicle speed, effective communication can be achieved at a distance of 300m with a good and relative constant data rate (5 Mbit/s). Our extensive literature review, has indicated that the value of 300m is also referenced in \[45\] as the indicative V2V communication distance using the IEEE 802.11p protocol.

Therefore, our study examines network graphs that capture wireless network connections established between vehicles separated by a distance of at most 300 meters.

\[C. \text{ Market Penetration}\]

The market penetration and the resultant background traffic has a significant effect on the network connectivity of urban traffic since it affects the VANET density. Thus, the spatio-temporal characteristics of the communication graph exhibited in each of the aforementioned mobility scenarios were evaluated using different market penetration values for VANET-enabled vehicles. We mainly study the network graph for 5 different penetration ratios, starting with only 20% of the total number of vehicles being VANET-enabled and gradually reaching 100% in 20-percentile increments. In some occasions we additionally study the network graph behavior in much lower penetration rates of 1%, 5%, 10% and 15%.

\[D. \text{ Stationary Road-Side Units}\]

In this work, we study extensively how the presence of RSUs influences the structure and evolution of the VANET communication graph. To achieve this, we extend the above realistic scenario in Los Angeles, by adding stationary RSUs. Assuming, that RSUs run IEEE 802.11p in addition to any other protocol, their effective communication distance in our evaluation was set to 300m. We utilize the Wigle.net \[46\] online catalog in order to extract the position of Wi-Fi hot-spots in the area of study, which potentially could be utilized as RSUs. Wigle maintains a publicly available and constantly user-updated catalog of wireless networks throughout the US, with each network attributed with identification (SSID), location (latitude/longitude), and security (open/private) information.

\[^2\text{CVIS technology is using the CALM M5 ISO standard that incorporates the IEEE 802.11p PHY/MAC}\]
We developed a tool to extract all open Wi-Fi Access Points (AP) in the area of study and placed them on the map by converting the GPS cylindrical coordinates to Cartesian plane coordinates. This process resulted in 427 APs that emulate the existence of RSUs in our study.

### Table I: Simulation setup parameters

|                      | Shanghai | Los Angeles |
|----------------------|----------|-------------|
| Trace Type           | Real     | Realistic   |
| Area Size            | $4\,Km^2$ | $4\,Km^2$   |
| Vehicle Density (veh/lane/Km) | n/a     | 10          |
| Average Vehicle Speed (m/s) | 4.72    | 3.12        |
| Total Vehicles       | 704      | 7000 (per sec) |
| Vehicle Transmission Range |          | 300m (802.11p) |
| RSUs                 | n/a      | 427         |
| RSU Transmission Range | n/a      | 300m        |
| Penetration Ratio    | 1%, 5%, 10%, 15%, 20%, 40%, 60%, 80%, 100% |
| Simulation Time      | 7200 sec (1000s warm-up) |
| Snapshots Interval   | every 1 second |

### E. Testbed Overview

Each of the above scenarios runs for 2 hours (7200 sec). We allow a 1000 second warm-up period at the beginning before obtaining any measurements in order to achieve some level of stability in the network. Consequently, we study snapshots of the VANET communication graph taken every 1 second. In total, for the above 2 mobility scenarios (Shanghai and Los Angeles), the different penetration ratios and the 1 complementary RSU scenarios (RSUs were not considered for real traces), a total 167400 snapshots of the VANET communication graph were recorded. Table I provides an overview of the evaluation testbed.

### V. Observations

This section presents the findings of our study related to the laws governing the networking shape of vehicular connectivity in both real and realistic scenarios. Note that our work does not examine the dynamics of the VANET communication graph under medium access problems (contention and interference) [47]. Our work shows that, based on factors such as: (i) mobility pattern of vehicles, (ii) a given transmission range, and (iii) the existence of RSUs, there is a possibility that a number of communication links could be established (if required) at a given point in time. The set of all such
possible links, dictate the characteristics of the VANET graph, and knowledge of such information is crucial in the design/operation of routing and data dissemination protocols. However, the particular of how these links (i.e the shared medium) are accessed, is the work of MAC protocols, something which is out-of-scope of our work.

In the interest of space and clarity, we present the analysis results for 1 hour (3600 sec). The respective scenario and simulation parameters are indicated accordingly. The data analysis was performed on a machine with an 8-core Intel(R) Xeon(R) CPU @ 2.83GHz and 24GB RAM, using the aid of two graph/network analysis frameworks, JUNG [3] and SNAP [4] The complete analysis duration of each individual graph varied between 5mins and 32hrs, depending on the selected penetration level.

A. Network Analysis

The spatio-temporal evolution of the VANET is primarily influenced by two interrelated factors: i) the number of vehicles and stationary RSUs that participate in the network at any given time instance and, ii) the effective transmission range of the wireless communication hardware in use. Initially, to gain elementary knowledge on this evolution, we study how the size of the VANET (number of edges and consequently the number of connections) changes as a function of the above factors. To compensate for the fact that, the realistic scenarios under study, follow a steady-state behaviour - that is the number of vehicles remains constant over time - we opt to study the VANET evolution as a function of different market penetration ratios and transmission ranges. Figures 2(a) and 2(b) illustrate the VANET size over different market penetration ratios (P) and transmission ranges (Tx) respectively for the Los Angeles. Specifically, we observe the VANET graph is growing almost linearly as the penetration rate and transmission ranges increase, an evident behaviour in all the examined scenarios irrespective of time. Figure 2(c) illustrates the VANET size over time in the real scenario (Shanghai), as more vehicles enter the map.

In agreement with the findings of [17], we observe that average node degree increases as the VANET grows. As expected, increasing the penetration ratio incrementally from as low as \( P=1\% \) to \( P=100\% \),

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3JUNG: Java Universal Network/Graph Framework - http://jung.sourceforge.net (accessed August 2011)
4SNAP: Stanford Network Analysis Platform - http://snap.stanford.edu (accessed August 2011)
results in an increase of node degree (see Table II), however this rate of growth, decreases linearly. This finding is quite important, since it provides the ability to estimate the future size of a VANET, given forecasts of V2V and V2I technology penetration. Such estimates allow engineers to plan-ahead the network capacity, as well as, make fault tolerance and recovery provisions. It is worth noting that, despite the small values of node degree observed in the Shanghai scenario (due to the sparse nature of mobility traces), the node degree increase rate follows the similar trend of the Los Angeles scenario.

A sound observation that occurs by examining the degree distribution of both scenarios (figures not shown in the interest of space) is that VANET graphs demonstrate a regularity that is unlikely to be a coincidence. Specifically, we observe that at low penetration ratio, the degree distribution of VANETs is skewed. As an example, for the Shanghai scenario and $P < 60\%$, VANET graphs have the following characteristics: the distribution $P(k)$ of node degrees $k$ follows $P(k) \sim k^{-\gamma}$, with exponent $\gamma$ often lying between 2 and 3. This indicates that low penetration rates tend to fragment the VANET to several small clusters, while high penetration rates favor the formation of a single large cluster and few smaller clusters at its surrounding (cluster analysis follows in V-B). An increase in the penetration ratio, improves the network connectivity considerably, as each individual node is able to establish connections with even more vehicles. Figure 3 obtained using [48], provides a zoom-in snapshot on the shape of the VANET established in the simulated area of Shanghai and gives a visual indication on the effects of penetration rate in the formation of clusters.

Examining the degree distribution of the real scenario even further, we observe that in the case
of $P=20\%$, the average node degree remains significantly low. Particularly, less than 50\% of the total vehicles are connected to more than 4 neighbour vehicles. As a matter of fact, our study shows that these vehicles are the ones located at the proximity of densely populated intersections (4-way or higher intersections).

Our study shows that the introduction of stationary RSUs in cases of low penetration provides a significant potential to improve vehicle connectivity. Evidently, RSUs improve inter-vehicle connectivity significantly at low penetration ratios ($P < 20\%$), in contrast to higher vehicle densities where connectivity remains more or less constant. Considering the Los Angeles scenario when $P=10\%$ and after the deployment of 427 RSUs, the median node degree is doubled. Table II presents the node degree statistics under the presence of RSUs and different penetration ratios.

Next, we examine the evolution of the VANET graph effective diameter over time. Primarily, we find that the effective diameter of both the real and realistic scenarios follows the diameter of the biggest cluster in the network. For the Los Angeles scenario, the effective diameter exhibits high variance for $P < 10\%$ without exceeding 9 hops. Exceeding $P=10\%$, the effective diameter stabilizes to around 5 hops.
TABLE III: Effective Diameter, Node Degree and Avg. Degree of Separation under different penetration ratios.

For the Shanghai scenario, when $P < 40\%$, the effective diameter is also low and quite stable (2 hops). This is due to poor network connectivity caused by the presence of several small clusters. On the other hand, as the penetration ratio increases over $P=40\%$, the effective diameter increases and stabilizes to around 9 hops.

Continuing our network analysis, we find that the VANET exhibits small world properties. This arises from the observation that the average degree of separation (i.e., mean shortest path length between pairs of nodes) over time, remains low for all the scenarios we studied. For instance with $P = 100\%$, the average degree of separation between two vehicles is 3.3 hops for the Los Angeles area and 5.2 hops for the Shanghai area with smooth changes as time progresses and with very small variability. The presence of RSUs has no effect on the average degree of separation, when $P > 10\%$. Moreover, in both scenarios our analysis has indicated that the average degree of separation increases linearly with the average geographic distance of node pairs but never exceeds the above values.

Table III presents the VANET connectivity under different penetration ratios for the Los Angeles and Shanghai areas. For the Los Angeles scenario, the effective diameter and the average degree of separation do not present significant changes. This is due to the fact that the number of vehicles (even when $P=20\%$) is high enough to allow the VANET fusion, that is, many clusters which are present when $P < 20\%$, are now fused into larger clusters, thereby enabling even more vehicles to communicate among them. For the Shanghai scenario, this fusion process is evident when $P > 20\%$, and consequently, the effective diameter and average degree of separation do not present significant changes for $P \geq 80\%$ (not shown here).
**Lessons:** 1) The degree distribution of VANETs is positive skewed at low value of penetration ratio. With the increase of penetration ratio, this skewness fades as the majority of nodes have high degree and network connectivity improves. 2) The VANET communication graphs exhibit small world properties. This indicates that most node pairs are connected by at least one short path, indicative by the average degree of separation which remains low, independent of penetration ratio. In addition, there are several vehicles (hubs) in the network with a very large degree, that mediate large path lengths between other node pairs.

These observations are useful since they provide indications about the richness of the network connectivity. Gossip protocols [49] should be investigated in order to take advantage of small-world properties, and especially scale-free ones, in order to efficiently disseminate information in vehicular networks. In addition, the network’s density makes the use of power transmission adjustment mandatory. The difference in a VANET setting is that this procedure must be *continuous*, and can not be decided once in advance. Such continuous power adjustment is not easy to achieve, unless it is done on a per-road-segment basis (e.g., CVIS platform).

**B. Cluster Analysis**

Network analysis performed in the previous subsection provided evidence that vehicles are partitioned into several clusters. Therefore, it is imperative to perform a thorough study of these clusters and understand their properties as a function of time and transmission range. Later in this subsection, we look deeper into the VANET communication graph to examine the existence of communities (dense sub-graphs) and their dynamics.

As seen on Subsection [V-A] the penetration ratio influences significantly the number of clusters existing in the VANET. Specifically, for the real scenario, at $P=20\%$, the number of clusters is *approximately 5 times larger* than that for $P=100\%$. Moreover, in the former case the biggest cluster (in terms of membership) contains at most only 30% of the total vehicles. In such cases the placement of static RSUs can efficiently bridge fragmented parts of the VANET, reducing thereby the number of clusters and improving the overall end-to-end connectivity. For this scenario only, we simulated the placement of 427 RSUs in the area of
Shanghai, following the same density per $km^2$ as found in the Los Angeles area. The results indicated a reduction of up to 22% in the number of clusters present in the VANET is possible. On the other hand, when $P > 60\%$, the number of clusters remains constantly less than 7 (with low variability) with the size of each cluster being significantly large. The case of the realistic scenario however exhibits different behaviour from the above, with penetration ratio changes having minimal influence to the number of clusters present in the network. This can be accounted to the fact that vehicular density is significantly high, and a transmission range of 300m, even when $P < 20\%$, is enough to form 1 single large cluster, containing the majority of vehicles.

The **average clustering co-efficient** for the real scenario fluctuates around 68% for $P=100\%$ and gets smaller and notably variant as vehicle penetration decreases. In order to compensate to these side-effects and keep a relatively stable clustering co-efficient close to the above value, our study has indicated that a minimum density of 5 RSUs per $km^2$ is required. Concerning the realistic scenario the clustering co-efficient stabilizes to about 71% for all values of vehicle penetration. It is worth noting that, despite the difference in vehicle density among the two scenarios, the average clustering co-efficient remains relatively close and consistent. This denotes that once a specific level of vehicle density is reached in the VANET, the internal connectivity of the formed clusters is not affected by changes in the vehicle mobility pattern due to different underlying road topology. Nevertheless, even in low vehicle densities, the clustering co-efficient is a good indicator in terms of the connectivity of the nodes contained in the cluster. Hence, nodes that belong to a cluster with a higher co-efficient than others, will be prefered for the forwarding of information in sparse networks, since there is a higher propability of establishing a communication path.

As previously mentioned, when $P > 60\%$ the VANET graph is comprised of few clusters, mainly one large cluster containing the majority of vehicles and other significantly smaller clusters in its surroundings. To further understand the **biggest cluster** in terms of the number of vehicles, we choose to study its properties as a function of time and penetration ratio. To this end, Figures 4(b) and 4(a) present the biggest cluster geographic size in the areas of Los Angeles and Shanghai respectively, at the extremities
Fig. 4: Biggest Cluster Geographic Size vs. Time.

\((P=20\% \text{ } \& \text{ } P=100\%)\) of vehicle penetration. Initial observations indicate that the geographic size of this cluster exhibits similar behaviour in both areas, thereby concluding that the road topology has little or no effect on its structure and evolution. In particular, for \(P=20\%\) the biggest cluster occupies almost the whole Los Angeles area and approximately half of the whole Shanghai area. In low-vehicle density environments such as the one in Shanghai, the biggest cluster in terms of geography, tends to be small in population size, thereby being prone to changes (visible in the lower part of Figures 4(a)) due to the arrival and departure of vehicles. Interestingly, the utilization of RSUs allows the biggest cluster in the Shanghai area to expand massively in size and occupy \(\geq 87\%\) of the space (not shown in the aforementioned figure). On the other hand, the geographic size of the biggest cluster when \(P=100\%\), in the area of Los Angeles, presents a smooth and less variant change in time, while occupying almost 99\% of the given area. These levels of coverage are significant, since vehicles participating in the largest cluster, can disseminate information in large and remote geographic areas. In terms of cluster membership, in the Shanghai area, for \(P=20\%\), the biggest cluster contains between 10\% to 33\% of the total vehicle, while for the realistic scenario it contains more than 98\% of the total vehicles.

However, despite the usefulness of the aforementioned findings, the geographic coverage of the biggest cluster alone does not accurately capture its quality in terms of providing end-to-end connectivity and effective information dissemination. To complement the above information and better quantify the quality of the biggest cluster, we investigate its local clustering co-efficient as a function of time and market penetration ratio. We discover that at low vehicle densities, the biggest cluster co-efficient is quite variant.
and at several instances, is significantly lower than the average clustering co-efficient. As the penetration ratio increases the local co-efficient remains stable for both scenarios close to 70%. This observation is important since it indicates the high density of communication links in the cluster and subsequently the existence of almost-cliques in the network, despite the different underlying road topology.

We proceed our analysis by exploring the VANET communication graph for the existence of communities, that is groups of vehicles with more intra-communication links than inter-communication links. Given the high density of intra-communication links, information replication could easily be achieved, allowing communities to act as “data islands”.

Community analysis begins by investigating the modularity of the VANET communication graphs. Community modularity quantifies in the range of -1 to 1 the division of the graph into communities, with good divisions giving communities with dense internal connections and weak connections between different communities. We use the Girvan-Newman algorithm \cite{50} in order to identify the communities in VANET. For the real scenario, and at $P=20\%$, community modularity is quite variable and approximates the value of 0.8, indicating very good modularity. Despite the fact that in this case, the VANET exhibits excellent modularity in such conditions, this is misleading since low penetration ratios highly partition the VANET with the majority of vehicles belonging to different partitions and connected only to a handful of other vehicles. One could argue that such small communities could still be used to ferry information, but our study has shown that the highly dynamic nature of the VANET causes them to dissolve rapidly. On the other hand, as, for $P=100\%$ community modularity does not fall below 0.63.

Fig. 5: Community Modularity, under different penetration ratio.
As Figure 5 indicates, for the Los Angeles scenario community modularity stabilizes to approximately 0.48 and does not fall below 0.45, irrespective of the penetration ratio. This shows that even with lower modularity values, a good division of the VANET can be achieved and identify effectively the candidate “data islands”. Therefore, information dissemination protocols could ultimately use such structures to ferry information from one location to another with low probability of delivery failure.

**Lessons:** 1) At low penetration ratios and low vehicle densities, even a small number of RSUs per $Km^2$ are sufficient to maintain stable clustering coefficients over time. Maintaining a stable clustering coefficient allows node pairs in a cluster to maintain connectivity. 2) Strong cluster connectivity has the potential of improving end-to-end network connectivity in the presence of vehicles that bridge one or more clusters. At high penetration ratio, the clustering coefficient is very high and stable, and the introduction of RSUs has minimal benefits. 3) The clustering coefficient provides a good indicator about the connectivity of the nodes contained in the associated cluster, even in low vehicle density. As we will show in the next section, the clustering coefficient can serve as a criterion for selecting nodes that can forward information, at low vehicle density environments. 4) At low vehicle densities, the biggest cluster in terms of membership, does not correspond to better network connectivity. Consequently, nodes that belong to the biggest cluster may be less preferable for forwarding information. 4) VANET includes small communities which can be combined into larger sets of nodes that can also be meaningfully interpreted as communities.

The existence of communities implies that mobility models like the Random Way Point, which are based on types of random walks should be abandoned, because they do not produce clusterings of the vehicles and additionally they do not support the existence of “hub” vehicles that explain the distributions of the centrality metrics. Therefore, research towards richer models (e.g., [8]) must be conducted. Specifically, vehicles that belong in a community can be seen as a “data island”. This is widely observed in highways, where opportunistic protocols are used (e.g., Opportunistic Packet Relaying protocol - OPERA [51]). Therefore, since we also observe communities in urban environments, such protocols could also be adapted to urban environments. Furthermore, the existence of communities implies also that leader election algorithms will work successfully [52], especially if we incorporate the centrality metrics in their selection.
In addition, the existence of communities contributes on addressing the Maximum Coverage Problem [7].

Considering an area with an arbitrary road topology that must be equipped with a limited number k of RSUs, where to place them so as to maximize the dissemination of information? In points where borders of clusters exist, or in places where vehicle communities exist. Similarly, installation of RSUs is suggested in places where the nodes have low localized clustering coefficient (sparse network), and thus the delivery of messages would require a significant amount of time without the infrastructure.

C. Centrality Analysis

We proceed with our analysis by investigating the existence and spatial distribution of “central” nodes in the VANET communication graph. An initial observation for all the scenarios under study is the following: low penetration ratios do not foster the existence of ”central” nodes in the VANET. Recall, that the definition of lobby index implies that it is a generalization of node degree and some sort of ”simplification” of betweenness centrality. Therefore, this behaviour is expected, since as per our findings in the previous sections, in such situations the network is sparse and lacking the existence of large clusters, which in turn means that the majority of vehicles are connected only to very few other vehicles in their close proximity. However, this is not the case for the realistic scenario. Since vehicle density is significantly higher than in the respective scenario of Shanghai, vehicles have a considerable high value of lobby index with relatively variant in the course of time. The presence of RSUs, however, allows vehicle centrality to stabilize in the aforementioned case. Due to their static position, RSUs function as relay points through which communication paths between pairs of vehicles are established. Effectively, all RSUs have the same and significantly higher lobby index (around 240) from all other nodes in the VANET. Furthermore, our analysis has indicated that in scenarios with low penetration ratio, the vehicles that exhibit high lobby index than the rest vehicles, are the ones which are at the vicinity of a road intersection.

Figure 6 provides a snapshot of the Los Angeles and Shanghai areas divided into 64 rectangular zones, with each zone covering a geographic area equal to $250m^2$. For each zone, the betweenness centrality of the contained nodes is normalized, averaged and plotted on the z-axis. As Figure 6(a) depicts, at $P=20\%$ the majority of zones have average betweenness centrality very close or equal to 0.025. The zones which
Fig. 6: Geographic Distribution of Betweenness Centrality for Los Angeles and Shanghai.

Exhibit high levels of betweenness centrality are the ones containing densely populated intersections, which in turn allow vehicles to establish more connections to other vehicles from what would be the case in other locations. Unexpectedly, even with the much higher vehicle density of the Los Angeles scenario, the overall betweenness centrality of the nodes in the network is slightly increased, however, the geographic distribution is extended considerably.

**Lessons:**
1) Lobby centrality index is a better metric for identifying the "central" nodes in the VANET than the betweenness centrality metric. This is due to the statistic nature of the betweenness centrality metric, since most nodes have low and same betweenness centrality values.
2) Low penetration ratios do not foster the existence of "central" nodes in the VANET. The high mobility of vehicles, make graph-based topology-control methods (spanning trees, Gabriel/Yao graph, RNG) not appealing, whereas, clustering is preferable. Which could be the clusterheads? Not necessarily high-degree nodes, but those with large
betweenness centrality (if we need a few clusters), or those with high lobby centrality (if we need a lot of clusters). 3) The road network alone is not sufficient information to identify the positions of possible “significant” nodes in a VANET.

D. Link Analysis

The link level analysis of the VANET communication graph contributes to the prediction of the network-link lifetime. The number and duration of connected periods between any two vehicles, as well as the duration between successive connected periods is influenced by driving situations and vehicle speed. Table IV present the link-level statistics for the Los Angeles and Shanghai areas when $P=60\%$.

It is evident that higher vehicle densities, as it is the case of the realistic Los Angeles scenario, increase the time period in which two vehicles are in range of each other, thus allowing established links to have a longer duration. An increased link duration reduces the number of connecting periods between the two vehicles and consequently minimizes any overhead imposed by the process of re-establishing connections. Specifically, we observe that the duration of the connected periods in the Los Angeles scenario is almost 3x as the one in the Shanghai scenario. In general, results show the connectivity between two vehicles changes very frequently. In addition, it is worth noting that by comparing the mean and median, we can conclude that there is a significant high variability in the link duration values for both scenarios.

Figure 7 indicates that the number of connecting periods for both the real and the realistic scenarios remains relatively low for most vehicles. In particular, we note that there is a very low probability the same two vehicles will meet in excess of 3 times.

| Shanghai                  | Min | Max | Mean | Median |
|---------------------------|-----|-----|------|--------|
| Number of Connected Periods | 1   | 11  | 1.7  | 1      |
| Link Duration             | 1 sec | 4541 sec | 108.27 sec | 41 sec |
| Re-Healing Period         | 1 sec | 4550 sec | 370.16 sec | 47 sec |

| Los Angeles               | Min | Max | Mean | Median |
|---------------------------|-----|-----|------|--------|
| Number of Connected Periods | 1   | 43  | 2.39 | 2      |
| Link Duration             | 1 sec | 4503 sec | 393.44 sec | 226 sec |
| Re-Healing Period         | 1 sec | 4500 sec | 979.85 sec | 463 sec |

**TABLE IV:** Link level statistics for Shanghai and Los Angeles scenarios at $P=60\%$. 
Fig. 7: Connecting Periods CDF at P=60%

**Lessons:**
1) The network connectivity is highly dynamic and it is affected by the network density. Specifically, the link duration of vehicles is almost tripled at high vehicle densities, whereas, the connected periods is almost doubled at high vehicle densities. This implies that a limited number of "killer applications", (i.e., large data files transfer and real-time information dissemination) can be supported by VANETs. Nonetheless, as we will show in the next section, one way to increase the set of applications that can be supported is to enhance VANET routing protocols with VANET graph knowledge.
2) Most vehicles have low number of connected periods. This means that it is not required to re-initiate often the route discovery process in routing protocols. Also, the duration of connected periods is important for designing a routing protocol, since several applications in VANETs are governed by the duration of the connected periods and how frequently the path between vehicles becomes unavailable. Specifically, it can be utilized to provide information exchange resilience by estimating an upper boundary to the amount of information that can be exchanged between any given pair of vehicles.
3) The re-healing time between vehicles is large for both the real and the realistic scenarios in urban environments; this observation is useful since it can be used to indicate the size of message buffer and how long a vehicle should buffer the broadcast message before it rebroadcasts it to another vehicle. Also, this metric is useful for determining how frequently a vehicle should periodically send out the beacon messages so that the relay vehicles can be discovered without flooding the network. Finally, the re-healing time measure is a critical metric for implementing carry-and-forward protocols for VANETs. In these protocols, vehicles buffer the broadcast message for some period before broadcast it to other vehicles.
VI. IMPLICATIONS

In the previous section we conducted a thorough analysis of the spatio-temporal characteristics of a large-scale VANET graph and gained a deep understanding of its shape. The question that remains to be answered is whether this knowledge is indeed useful from an engineering perspective. In this section, we seek to answer this question by providing two known VANET routing protocols, VADD [15] and GPCR [16] with VANET graph information, to determine whether such information can improve their quality of service. We opted to use the above routing protocols, since each one is a member of a different family of VANET protocols with its own set of requirements [53].

A. VADD: Vehicle Assisted Data Delivery

VADD is a unicast, delay-tolerant protocol that uses beacon-driven geographic routing to forward packets from source to destination. It adopts the idea of carry-and-forward based on the use of predictable vehicle mobility, in order to achieve low data delivery delay in sparse networks. Having knowledge of the underlying road infrastructure through a static map, packets are forwarded along streets and routing decisions take place at intersections where vehicles select the next forwarding path (series of consecutive streets) to destination with the smallest packet delivery delay. Through a stochastic model that takes into consideration vehicle density on a road, road length and average vehicle velocity, the expected packet delivery delay can be estimated.

However, the authors of [54] have shown that VADD experiences performance degradation in packet delivery delay and drop rate under low-vehicular density conditions. Specifically, in such conditions, a packet carrier entering an intersection, may not be able to push a packet towards the optimal forwarding path, due to the fact that there no available vehicles on that path. Therefore, the packet is forced to be forwarded towards a sub-optimal path, which consequently leads to higher packet delivery delay or even higher packet drop rate.
B. GPCR: Greedy Perimeter Coordinator Routing

GPCR is a overlay, non-delay tolerant protocol that also uses beacon-driven geographic routing to forward packets from a source to destination. Similar with VADD, packet forwarding is performed along streets in a greedy manner and routing decisions are taken at intersections. GPCR takes advantage of the fact that streets and intersections form a natural planar graph and uses it as a repair strategy when a packet reaches a local optimum. Key to the routing process, is the detection of nodes (coordinators) located on an intersection, since GPCR does not rely on an underlying street map. To do so, GPCR employs two approaches: i) neighbor tables, where a node $x$ is on an intersection, if it has two neighbors $y$ and $z$ that are within range of each other but do not list each other as neighbors, ii) a correlation coefficient that relates a node with its neighbors w.r.t to their position.

C. Graph enabled VADD and GPCR

The goal was to enable each protocol to utilize the graph analysis information, during the routing process decisions, therefore minor changes were applied to the proposed algorithms. Primarily, the followings changes were performed to each aforementioned protocol - VADD: On each beacon period, a vehicle broadcasts along its geo-coordinates, information about its current lobby index, whether is a member of a cluster, and if so, the specific cluster size and clustering coefficient. During low vehicle density conditions, such information can be utilized by a packet carrier in a 3-step policy, as it arrives at an intersection and its time to to choose the next packet carrier. Particularly, on an intersection, if the current packet carrier, does not identify a candidate node which is en route to the packet destination via an optimal path (as calculated by MD-VADD), then in the presence of other less favorable nodes, the next packet carrier is selected to be the node that: (1) has the largest lobby-index value, or (2) belongs to a cluster with the largest cluster coefficient or (3) belongs to the largest cluster in terms of membership. This ensures that the packet will be handled to a node with higher network connectivity, and thus increase its chances to be routed to destination. GPRC: As in the VADD, on each beacon period, a vehicle broadcasts along its geo-coordinates, information about its current lobby index value. We select only the lobby-index to be broadcasted, since through Section V-C, we have observed that this metric can identify vehicles that are
on the close vicinity of a road intersection. In addition to the two native algorithms for detection vehicles on an intersection, we enable GPCR to detect such nodes using the lobby index value broadcasted on each beacon period. In essence, the lobby-index approach is a variation of the neighbor tables which not only identifies candidate coordinator nodes, but also provides a view of which candidate coordinator has the best network connectivity.

D. Implementation

To achieve the above, both VADD (MD-VADD variation) and GPCR were implemented from scratch under ns-3.11 [55], trying to remain as accurate as possible given the information provided in the original articles [15], [16]. Mobility traces used in network simulations, were analyzed a priori, second-by-second, in order to extract VANET graph information such as the lobby index values of nodes, cluster membership and clustering co-efficient. This information was fed to ns-3 at the start of the simulation, allowing each node, at any given time instance, to utilize it through queries to a God service. It is important to notice, that how such graph information is acquired and made available to vehicles in a real VANET (i.e cluster detection protocols, lobby index calculation) is out of the scope of this article.

|                | VADD               | GPCR               |
|----------------|--------------------|--------------------|
| Mobility Model | IDM, LC            |                    |
| Area Size      | 4000m x 5000m      | 6500m x 3500m      |
| Vehicles       | 150                | 900                |
| Vehicle Range  | 300m (802.11p)     |                    |
| Propagation    | Nakagami Propagation Loss |
| Simulation     | 3600s (600s warm-up) |
| Beacon Interval| 0.5s               |                    |
| Packet Senders | 15                 | 10                 |
| CBR Rate (pkt/sec) | 0.1 - 1   | 4                  |

TABLE V: VADD and GPCR Simulation setup parameters

Considering the modifications described above, we opted to record the packet delivery delay over the data sending rate for VADD and packet deliver rate over the communication distance for GPCR. Details about the simulation setup are provided in Table V. Figures 8(a) and 8(b) present the results of our simulations. The figures present the average values of each metric calculated over 5 runs of each simulation scenario, with different random number seeds.
We observe, that VADD has a considerably high packet delivery delay when the number of vehicle penetration is low (150 vehicles), which is consistent with the findings of [54]. By enabling VADD nodes to utilize graph information in their routing decision on an intersection, we record an average improvement on delivery delay of approximately 6%, throughout the data sending rate range. Indeed, through the ns-3 trace log we notice that when there are no nodes at the intersection which are considered as optimal candidates by the native VADD forwarder selection process, then lobby index information is sufficient to identify a sub-optimal node that will be entrusted with forwarding the packet at hand.

Concerning GPCR, we observe that by utilizing graph information, and particularly the lobby-index value, it is sufficient to identify vehicles which are on or at the vicinity of an intersection. Throughout the communication range, the packet delivery rate remains above 56%, with a maximum rate of 69%. It is worth to note, the utilization of such a simple graph metric for the vehicle detection process, gives results which are slightly less better than when utilizing the calculation of the correlation coefficient (CC).

Article [6] asked the question: which nodes will be the forwarders in routing? Our study is able to provide an answer to this: we can draw such nodes among those with high centrality value. These nodes are also perfect candidates for message ferrying in case of network partitioning. Similarly, nodes with high lobby index are ideal for carrying out the rebroadcasts so as to spread the message to many recipients with as few rebroadcasts as possible. Moreover, for applications requiring awareness of the positions of other vehicles through periodic beacons, or the distribution of traffic related data through periodic beacons, the exploitation of the more ”central” vehicles for these tasks could relieve the network from redundant
broadcasts and reduce the collisions.

VII. CONCLUSIONS

This paper provides a complete study of the topological characteristics and statistical features of a VANET communication graph. Using both real and realistic mobility traces, we study the networking shape of VANETs in urban environments under different transmission and market penetration ranges. Given that a number of RSUs have to be deployed for disseminating information to vehicles in an urban area, we also study their impact on vehicular connectivity. Specifically, our work addresses the following questions: Which are the statistical properties that characterize the structure and behavior of vehicular networks? How do VANET graphs evolve over time? Can be identified communities in vehicular networks? We view our findings as particularly important since the obtained results have a wide range of implications upon the creation of high-performance, reliable, scalable, secure, and privacy-preserving VANET technologies.

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