A Cautionary View of Mobility and Connectivity Modeling in Vehicular Ad-Hoc Networks

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Abstract—Motivated by the recent surge in vehicular ad-hoc network (VANET) research and the promise of high-impact applications such as safety, navigation and infotainment services, we consider the impact of mobility mis-modeling on the design and development of this class of distributed systems. Focusing on urban environments, we use a state-of-the-art car traffic simulator to extract some of the key connectivity metrics relevant for the design of a vehicle-to-vehicle traffic information system. We compare such metrics against those obtained from popular mobility models, such as the random way point model and the Manhattan mobility model. Our results reveal striking differences in the connectivity profile of the network, thus casting some doubt on the adequacy of simple mobility models for the development of future VANET protocols.

I. INTRODUCTION

The future and success of Vehicular Ad-hoc Networks (VANETs) as wireless carriers for high-valued services is largely dependent on our ability to capture and exploit the characteristics of vehicle mobility and the resulting connectivity profiles. At the same time, it is reasonable to assume that these key properties will be expected to match technical requirements that can vary a lot depending on the envisioned application scenarios. Distributed safety systems will require almost instantaneous dissemination of alarm messages and distress signals upon detection of accidents or road hazards. At the other end of the spectrum of applications, large-scale sharing of traffic information can be performed at low rates and higher delays, whereas information broadcasts, entertainment services and mobile internet access require higher bandwidth and adequate quality of service. In all cases, the main limitations will no doubt arise from the physical properties of the wireless medium and from multiple transmitters and receivers moving at various speeds along highways, avenues and streets.

In an effort to grasp at least part of this complex mix of limiting factors, mobile ad-hoc network (MANET) research has produced a number of mobility models, in which nodes are placed randomly on a prescribed area and make random decisions about where to move next and at what speed to proceed. Beyond the classical random walk, the random way point model has been widely used to draw inferences on the behavior of wireless connectivity among mobile peers. In other contributions, simulated nodes move along the edges of a Manhattan grid, in an attempt to reflect the trajectory constraints induced by a road network. The simplicity and tractability of these models render them very appealing from the point of view of implementation, which is a likely explanation for their popularity in the existing literature.

Being concerned that available MANET models may not be sophisticated enough to capture the subtle aspects of vehicle mobility and wireless connectivity that are crucial towards a thorough understanding of VANETs in urban environments, we set out to compare their performance with the results obtained from highly realistic traffic simulation. Our main contributions are as follows:

- **Characterization of mobility and connectivity in VANETs:** We combine a realistic traffic simulator (the DIVERT framework) and tractable communications models to provide a more accurate characterization of the mobility and connectivity patterns of vehicles in an urban environment;
- **Connectivity Parameters for a VANET information system:** Focusing on the dissemination of traffic information between vehicles, we show how to translate application requirements into critical connectivity metrics that are amenable to analysis via our simulator;
- **Critical comparison of mobility models:** We contrast the connectivity profiles obtained from popular mobility models such as the random way point model and the Manhattan grid mobility model with the results from our combined traffic and communication modeling approach, thus highlighting some of the deficiencies of existing mobility tools for VANET research. We focus on very sparse scenarios (less than 15 vehicles per square kilometer), where the mobility pattern is particularly stringent for the correct characterization of network connectivity.

The remainder of the paper is organized as follows. First, Section II describes the DIVERT framework and gives an overview of some of the existing mobility models, providing formal descriptions for those that are relevant to our work. This is followed by a survey of related work in Section III. Section IV addresses different metrics to assess VANET connectivity in a meaningful way. The core of our contribution can be found in Section V, which provides a methodology to obtain meaningful data about wireless connectivity and information dissemination in VANETs, and discusses an extensive set of simulation results. Finally, Section VI concludes the paper.
II. MOBILITY MODELS

A VANET is a specific type of a MANET, distinguished by the type of scenario (i.e. road network) and by the high mobility of the nodes (i.e. vehicles). The movement of each vehicle is thus confined to a road network, restricted by the topology, the traffic signs and by the interaction with other vehicles. This leads, when comparing to a MANET without these geographic restrictions, to an increase both on the number of times each node stops and on the duration of such pauses. This behavior has a great impact on the network connectivity.

When simulating a VANET environment, these issues must be taken into account and be reflected by the mobility model, otherwise one may end up with misleading results [1]. Taking two of the most widely used mobility models in MANET research, Random Waypoint and Manhattan Grid, we compare the values of relevant connectivity metrics obtained via these models with those yielded by a state-of-the-art urban traffic simulator, DIVERT (section II-C), operating based on the road map of a real city. The need to study connectivity implications of using different models for mobility is well illustrated in Figure 1, which depicts the location of nodes in a space of identical area and aspect ratio (width vs. height) after a 180 seconds simulation using: a) Random Waypoint; b) Manhattan Grid; and c) DIVERT. One can observe very different distributions for the nodes, even when the parameters of each model (as we shall explain later) have been set as similarly and fairly as possible.

A. Random Waypoint Model

The Random Waypoint Model (RWM) [2] describes the movement pattern of a mobile node (MN) in a two dimensional, circular or square, open area \( A \). In this model, a MN begins in a position, distributed uniformly over \( A \), and remains there for pause time \( t_{\text{pause}} \), chosen from an interval \([0, \text{maxpause time}]\). Then, it randomly selects a destination point in \( A \) and moves towards it on a straight line, at a constant speed distributed uniformly between \([v_{\text{min}}, v_{\text{max}}]\). The MN stops for \( t_{\text{pause}} \) seconds and the process starts again. RWM properties have been extensively studied [3], [4]. In [5], regarding its spatial node distribution, it has been shown that MNs in this model suffer from a “border effect”, i.e. when starting a new movement at a position near the border of the simulation area, they will frequently move back towards the center. As a result, at a given simulation time \( t \), it is more probable for a MN to be in the center of \( A \). As \( t \) increases, node distribution converges to a steady state, where nodes are non-uniformly distributed over \( A \), with the majority of the MN at the center and few at the borders. To cope with this transition phase, a warming time should be used [6].

B. Manhattan Grid

The RWM is limited in the sense that it does not capture some important characteristics like spatial constraints. The Manhattan Grid (MG) mobility model [7] by emulating the movement pattern of vehicles in a Manhattan-like map allows for the evaluation of this aspect. The map is then composed by vertical and horizontal roads, with one lane for each way. The MNs are allowed to move along the grid, being able to change direction at every intersection, with a given probability. The speed is chosen randomly from an interval \([v_{\text{min}}, v_{\text{max}}]\) and can be updated every \( \text{updateDist} \) seconds. In the first definition of MG [8], the MNs are initially supposed to be distributed uniformly over the map. However, some implementations, like the BonnMotion Framework introduced in III, place all MNs in position \((0,0)\). To overcome this limitation, they also allow for the parametrization of a warming time, used to cut off the initial transient phase of the simulation.

C. DIVERT Framework

DIVERT [9] uses a detailed characterization of traffic signs that are exactly meant to affect mobility, such as speed limits, traffic lights or yield priority signs. Furthermore, DIVERT uses a parametrized origin/destination matrix, over which an algorithm of shortest-time path, which uses statistical information of measured speeds on roads from previous simulations, and computes the routes followed by each vehicle, in sharp contrast to the random selection of routes of the aforementioned models. One situation that should be synergistic with the communication between vehicles is when the vehicles travel on the same road in different lanes with opposite directions. Detail at this level is very important and is offered by this simulator. In DIVERT, micro-mobility is considered, such that the movement and velocity of a vehicle are constrained by the other vehicles. This is modeled using different techniques like the car-following model [10] or the lane-changing model [11]. The reader can get a sense of the realistic feel of DIVERT simulations through a short video available from [12].

III. RELATED WORK

Although VANET mobility in urban environments is arguably not yet fully captured by existing models, extensive studies have been done regarding the comparison between mobility models for MANETs. For example, [7] uses several mobility models and tries to answer whether and how mobility affects the performance of the routing protocols for MANETs, whereas [13] analyzes the delivery ratio and packet delays sensitivity concerning specific vehicular movement constraints and outlines the impact of the clustering effect at intersections in contrast with other aspects like the simulation of multiple lanes. In [14], two mobility models simulate the behavior of vehicles in the presence of stop signs and traffic lights. The study highlights the importance of the clustering at intersections and the need to use mobility models that take into account specific aspects of urban environments, when simulating VANETs. [15] compares the RWM with a novel mobility model based on the motion of vehicles on real street maps. By evaluating the performance of DSR [2], it concludes that although RWM is a good approximation of the reality in some situations, a more realistic model should outperform it. For these studies, various implementations of mobility models were used (e.g. GrooveNet [16], STRAW [17], BonnMotion [18]). Here we highlight BonnMotion Framework (BM).
as it will be used in Section V for our evaluation of RWM and MG. BM allows for the creation and analysis of mobility scenarios. This framework implements several mobility models, including the models introduced in the previous subsections. It only considers basic motion constraints, not considering any micro-mobility. BM generates simple movement patterns into trace files that can then be exported to NS2 [19] or be easily integrated with another network simulator.

Our work differs from previous literature in a number of points. First, we analyze connectivity of the distinct mobility models using extended graph theoretical metrics, that capture the cumulative topology of a graph with mobile nodes. Secondly, our connectivity analysis is targeted to high-latency tolerant applications, such as a mobile peer-to-peer network simulator. Third, we focus on very sparse scenarios, where the mobility behavior is much more determinant for the overall connectivity of the network. Fourth, these sparse scenarios are obtained through the simulation of very large areas, as the city of Porto (42 km²), in sharp contrast with previous works that focus on very limited areas.

IV. CONNECTIVITY OF VEHICULAR AD HOC NETWORKS

This section introduces the main concepts and definitions in the context of connectivity in a vehicular ad hoc network. We describe the concept of node degree in a time interval and present a generalized notion of transitive closure of a graph, coping with node mobility. We also describe an example application protocol based on a vehicle-to-vehicle traffic information system supported by such a network.

A. Mobile Connectivity

To study the connectivity of a vehicular ad hoc network, we abstract its configuration at a given moment in time into a graph representation. Each vehicle corresponds to a node in the graph and we denote the set of nodes by \( \mathcal{U} = \{u_1, u_2, \ldots, u_n\} \), mapping its latitude and longitude (corrected through map-matching against the roads) into a point in the spatial reference system of the graph; links in the graph are determined by the wireless communication model that is used, which in our case is the purely geometric link model, and thus a node has links to all nodes that are within its circular transmission range. Such graphs are called unit-disk graphs, and are widely used to model wireless sensor networks [20]. Each link is represented by an unordered node pair \( \{u_i, u_j\} \) and we denote the complete set of links by \( \mathcal{L} \subseteq \mathcal{U}^2 \).

An important measure of the connectivity of these graphs is the average node degree, which is given by:

\[
d_{\text{avg}} = \frac{1}{n} \sum_{i=1}^{n} |\mathcal{N}(u_i)|
\]

where \( |\mathcal{N}(u_i)| \) is the cardinality of the set of nodes to which node \( i \) is connected, the neighbors of node \( u_i \), denoted by \( \mathcal{N}(u_i) \). Typically, in a vehicular environment, such instant connectivity degree is very low, because of the short range of communication of vehicles. However, the mobility of nodes in a short time interval can significantly improve this degree, with a minor sacrifice of the freshness of data transmitted by vehicles. In [21] we defined the degree of a node \( u_i \) moving in a time interval \([0...t]\) as follows:

\[
d(u_i)[0...t] = \left| \bigcup_{j=0}^{t} \mathcal{N}(u_i)_{j} \right|
\]

where \( \mathcal{N}(u_i)_{j} \) is the set of neighbors of \( u_i \) at instant \( j \). In DIVERT simulations, one \( j \) step corresponds to one second.

B. Transitive Connectivity

Information exchange in a vehicular ad hoc network happens not only between nodes directly connected but also through transitive connections, also called multi-hop connections. Care has to be taken when considering mobility together with transitive connectivity. Consider for instance that \( \mathcal{N}(u_1)_0 = \{u_2\}, \mathcal{N}(u_2)_0 = \{u_1\}, \mathcal{N}(u_2)_1 = \{u_3\} \) and \( \mathcal{N}(u_3)_1 = \{u_2\} \). At \( t = 0 \), \( u_1 \) and \( u_2 \) are connected and can exchange information. At \( t = 1 \), \( u_2 \) and \( u_3 \) connect, and \( u_3 \) will receive information from \( u_2 \) that includes the data \( u_1 \) sent at \( t = 0 \), but \( u_1 \) will not received any information from \( u_3 \). In this case, we consider that \( u_3 \) is transitively connected to \( u_1 \) but not vice-versa. Links in the mobile graph become directed, while in the static model they were undirected.

We generalize the set of links for a mobile graph in an interval \([0...t]\) to a set of triples of the form \( \{u_i, u_j, t'\} \), for \( t' \) in \([0...t]\) (e.g. \( \{u_1, u_2, 0\} \)). The set of links is denoted by \( \mathcal{L}' \subseteq \mathcal{U}' \times \mathcal{U}' \times [0...t] \) and we consider the following rule to compute the transitive closure \( \mathcal{L}'' \) of \( \mathcal{L}' \):

Fig. 1: Snapshots of simulations using different mobility models (RWM,MG,DIVERT)
∀u₁, u₂ ∈ U, t' ∈ [0...t], \{u₁, u₂, t'\} ∈ L** →
\{ u₁ ∈ N(u₂) \}
\exists u₃ ∈ U, \{u₃, u₂, t'\} ∈ L' ∧ \{u₃, u₁, t''\} ∈ L''' ∧ t' ≥ t''

The second part of this rule essential says that transitive paths have to follow a timed order on the links. An algorithm to compute this connectivity has been presented in [21].

V. Connectivity Evaluation of Mobility Models

In order to study the connectivity profiles of each of the three mobility models presented, we performed 50 simulations of each model, with two variations of the communication radius, in a total of 300 simulations. We tried to parametrize each of the models as identically as possible. The first parameter was the area of the simulation. Given that DIVERT simulations were performed over the city of Porto, we computed the total area of the city, deriving the value of 41.65 square kilometers. We also computed the maximum width and height of the map of Porto, deriving an aspect ratio of 2.1 : 1. We then defined a rectangle with that same aspect ratio and area. This was used for the simulations using RWM.

MG used an identical rectangle, but in addition we computed the total length of the roads in Porto’s city map, deriving a total of 650 kilometers. We then defined a square grid with that same length, creating the road map used in MG simulations. An important aspect in this grid is the distance between consecutive parallel roads. The derive value was of 128 meters. Our disk based network model, which is parametrized only by the radius of the disk, is clearly affected by the fact that the radius is or is not larger than the distance between consecutive parallel roads. We thus performed simulations with 100m and 150m to analyze the two possible scenarios in MG. Back in Fig. 1 we represented the empty rectangle of RW, the road structure of MG and the Porto’s road map.

An important metric in VANET experiments is the density of vehicles per square kilometer. Our experiments where done using 500 vehicles in RWM and MG. In DIVERT we used two types of vehicles, vehicles that are used as communication nodes, in an identical total of 500 vehicles, and vehicles that just affect the mobility pattern of those 500, in a total of 4500 vehicles. Given that the Porto city area is of 41.65km², we get a density of 12 communicating vehicles per square kilometer, for all of the models. In order to provide a more intuitive indication of the density, we translate the above density value into the h metric of average inter-vehicle distance, proposed in [22], as follows. The total length of all the road segments in the simulated road network is of approximately 650 kilometers. Thus \( h = \frac{650}{500} = 1.3(km) \). Clearly, our simulations are performed in very sparse scenarios, where the differences in the mobility models become critical for the connectivity of the network.

Another parameter in our simulations relates to the speed of movement of the nodes in each of the models. Again, we used DIVERT simulations to compute the average and maximum speed of the vehicles, deriving the values of 13.7 m/s and 17.0 m/s, respectively. We then used this values to parametrize RWM and MG models. For the simulation of the RWM and MG we used the BonnMotion Framework mentioned in III.

We ran the simulations for 180 seconds, using a warm up time of 3600 seconds for MG and RWM, and 60 seconds for DIVERT. This shortest warm up time for DIVERT is related to the realistic routes of the vehicles, that would leave the city of Porto if we used an warm up time of 3600 seconds. We analyze the connectivity of each model using the previously explained notions of neighboring nodes in a time interval and its transitive closure. Figure 2 presents our results for communication radii of 100m and 150m. We plot the average percentage of nodes reachable by each node, in a varying interval of time, from 0 seconds to 180 seconds. If we consider the topmost curve of the plots and its value at the end of the time interval (180s), where the latency of data is as large as three minutes, then these differences between the three models are not dramatically different for 150m: \( 91\%, 99\%, 97\% \) for RWM, MG and DIVERT, respectively. With 100m radius this differences are more noticeable: \( 73\%, 89\%, 94\% \). If we observe the evolution of that topmost curve for a communication radius of 100m, we can see very significant differences in the connectivity profiles for each of the models. At 90s, for instance, RWM and MG present values of 25% and 10%, respectively, while DIVERT yields an average percentage of node connectivity of 59%.

Regarding the 150m simulations, where inter-block communication is possible in MG, the differences in the evolution of the topmost curve are much less clear. For the same value of 90s, we get averages of \{67%, 93%, 88%\}, for RWM, MG and DIVERT, respectively. Inter-block connectivity in Manhattan Grid clearly boosts connectivity, but we should not expect such communication to happen in realistic urban scenarios, because of fading caused by buildings.

We also plot the contribution to the average percentage of node connectivity by connections using different numbers of hops, which we group in distinct colors/fill patterns. Here the differences between the simpler models and DIVERT are striking. Using just up to four-hop connections, DIVERT is able to reach more than 60% of average connectivity, with a 100m radius, and almost 80% with a 150m radius. RMW reaches just 21% and 42% for 100m and 150m, respectively, while MG obtains 13% and 32% for the same radii. These are important observations with deep impact on the design of protocols for information dissemination in VANETs. Based on this result we could define protocols which limit information re-broadcast considering the number of hops, achieving high connectivity while mitigating redundancy and interference.

VI. Conclusion

Concerned with the potential inadequacy of widely used MANET mobility models for capturing the specific properties of VANETs in urban environments, we compared the connectivity profiles obtained via the random way point model, the Manhattan grid topology and a more realistic approach based on a large-scale traffic simulator. Our research
took into account multi-hop connectivity and targeted delay-tolerant applications in sparse networks. Under these general assumptions, which match the current ramp-up phase with low penetration of vehicular communication technologies, our findings are unequivocal: classical mobility models do not lead to realistic connectivity profiles. We believe this is an important observation, which could have a deep impact on the design of protocols for information dissemination in VANETs.

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Fig. 2: Connectivity analysis