Urban Connectivity Analysis of VANETs through Stereoscopic Aerial Photography

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***Abstract*—Connectivity analysis of Vehicular Ad Hoc Networks (VANETs) involves the study of static and dynamic characteristics of the network. Realistic mobility models are essential for both aspects, in order to produce valid configurations of the position of vehicles in one static instant, and to dynamically move such vehicles in an interval of time. Focusing on static connectivity evaluation, we extend the state-of-the-art of the realism of urban mobility models for VANETs, by proposing and implementing an analysis based on a stereoscopic aerial survey over a large European city. Our static connectivity metrics show important differences compared to the model and simulation based results described in the VANET literature.**

I. INTRODUCTION

VANETs will have a substantial impact on the act of driving in a near future. The importance of this new type of networks is acknowledged by the vast work published in the last years. Given the obvious difficulty in studying VANETs due to the absence of large-scale deployments, which are fundamental to study phenomena such as broadcast storms [1] or applications related to traffic optimization [2], [3], simulation-based research is the only choice available to address and validate the design of protocols in this context. The state-of-the-art of mobility models for VANETs is still distant from realistically simulating traffic in large-scale urban scenarios, and several pitfalls have been pointed-out for such simulation-based studies [4].

In this paper we describe an urban mobility approach that used 10,566 actual cars and trucks to obtain a realistic model of VANET connectivity in a typical European city, resorting to an aerial perspective over the city of Porto, in Portugal. The idea of using aerial photography as an alternate way to study the traffic model is not new and was used in [**?**], [**?**] and [**?**]. However, to the best of our knowledge, it has never been used in the context of connectivity analysis of VANETs.

II. DESIGN AND EVALUATION

To obtain such a large-scale realistic view of connectivity in an urban VANET, we used the data collected in a stereophotogrammetric aerial survey of the city, and processed such data to extract the relevant information for VANET connectivity analysis, namely the precise location of vehicles, its direction, speed and the type of vehicle (divided in cars and trucks). This data was provided by InfoPortugal S.A. company. Table I provides some relevant data about the aerial survey.

TABLE I
PORTO'S AERIAL SURVEY DATA

Aircraft	
Model	Cessna T210L Centurion II
Engine	300 HP Turbocharged
Autonomy	5.5 hours
Avg. operating speed	300 km/h
Max. operating altitude	8.700m
Camera	
Model	IGI DigiCAM H/39 RGB
Resolution	39 MPixels (7216*5412)
Lens	Hasselblad 80mm/2.8
Angle of view (d/h/v)	41°/33°/25°
Flight details	
Date	Wed 2nd April 2008
Avg. altitude	2815m
Avg. speed	241km/h
Total number of images	99
Total number of rows	9
Consecutive images lag	5.5s
Cons. images overlapping	69.84%
1st image time	13h53
Last image time	15h54

The company's latest flight over the city of Porto took place on Wednesday, April 2nd, 2008, between 13h53 and 15h54. In such an aerial survey, high quality photos are taken in a stereoscopic fashion, meaning that two or more images are shot from slightly different points, enabling the derivation of topographic information. With each image file having georeferencing and time metadata associated with it, such stereoscopy can also be used to accurately derive the traveling speed of vehicles, as shown in Fig. 1. The covering of the city is done in several rows, taking several snapshots, with each snapshot covering an area of just 2.09km^2 from a total of 41.3km^2 of the entire city. It is then clear that the positioning of all vehicles in the entire city is not obtained in a single momentum. However, we opted to analyze the entire city, considering that the vehicular distribution on the different images should be quite similar on the time interval considered. Indeed, if we choose the image with the most vehicles as the base image, and weight the time lag of each image, with relation to the base image, on the number of vehicles, we obtain an average lag of just 23 minutes. We have vectorized

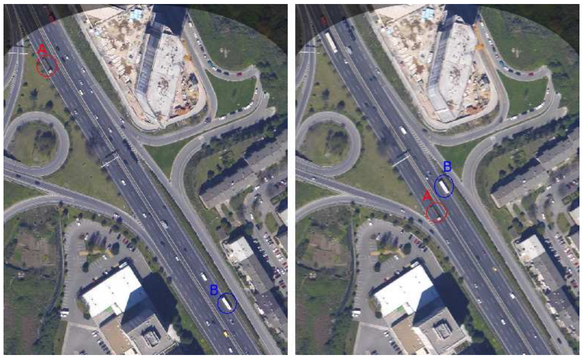

Fig. 1. The dimension of time allows perceiving the speed of vehicles A (88km/h) and B (68km/h).

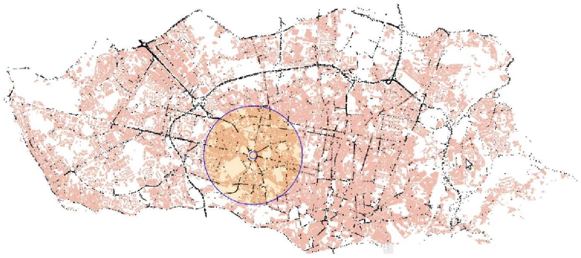

Fig. 2. Spatial distribution of buildings and of moving vehicles in the city of Porto at post-lunch time. We highlight a point in the center of a main roundabout in the city, and a 1000m circular area, to be used in Section II.

a total of 10,566 vehicles, corresponding to a density of 255 vehicles per square kilometer. Fig. 2 shows the spatial distribution of these vehicles over the road map of Porto. A more useful zoom-able webmap with more information is available at: http://drive-in.cmuportugal.org/stereoscopy/.

Regarding the realistic modeling of wireless communication, we used the data from the same aerial survey to identify a layer of buildings in the city, shown in Fig. 2, and implemented a range model that accounts for the obstructions caused by this layer on signal propagation. Buildings in the city of Porto account for 21% of the area, making it essential to consider this layer in the connectivity model. Furthermore, 93% of this area is contained in a buffer of 50m of the roads, thus affecting very much the signal propagation of road-based communication. The model we used in this paper is based on a direct Line-of-Sight (LoS) between two vehicles, 250m, or by the obstruction of this LoS through a building, 140m. Any two vehicles communicate if and only if they are within the corresponding transmission ranges. This same model has been used in [5].

In the current paper we focused on the analysis of static network characteristics. We want to understand how connected are vehicles in the network at a given point in time and if the network is connected how well-connected it is. Hence, two metrics of interest are:

- Network connectivity – the maximum number of vehicles that are connected at any given point in time. Two vehicles can be connected either directly or indirectly (via a multi-hop route). Formally, network connectivity is defined as

  $$NC(t) \quad \triangleq \quad \max_i \sum_j A(i,j,t) \qquad (1)$$

  where $A(i,j,t)$ is a connectivity indicator which takes on the value of 1 if a path is available from Vehicle i to Vehicle j at time t, and 0 otherwise.

  This metric is crucial for message dissemination applications as it directly translates to "reachability" when an omni-directional broadcast is used. Hence, it allows one to determine whether such messages reach all vehicles and identify whether the network disconnection is a serious problem in urban vehicular networks.

- Path redundancy between two vehicles – the maximum number of node-disjoint paths between two connected vehicles. The redundant paths are node-disjoint if they do not have any common nodes (or edges). Let $p_{ij,k}$ be the kth path connecting Vehicle i and Vehicle j. One may write $p_{ij,k}$ using the following representation:
  - $p^N_{ij,k} = \{n_1, n_2, \cdots, n_m\}$ consisting of m nodes with $n_1 = i$ and $n_m = j$.

  Let $P^{N\text{-}dis}_{ij}$ be the set of all node-disjoint paths that connect Vehicles i and j.

  $$P^{N\text{-}dis}_{ij} \quad = \quad \{p_{ij,k} : p^N_{ij,k} \cap p^N_{ij,k'} = \emptyset, \forall k \neq k'\}$$

  Hence, the node-disjoint path redundancy are maximum $\left\|P^{N\text{-}dis}_{ij}\right\|$, where $\|A\|$ denotes the number of elements in the set A.

In contrast to network connectivity which merely captures the connectivity of a network (*i.e.*, whether network is connected), the path redundancy depicts the richness of network connectivity (*i.e.*, how many available paths between vehicles). Thus, it indicates how many duplicate messages will be received at a vehicle, implying how severe the broadcast storm problem is.

Fig. 3 presents the connectivity graphs between network nodes using the aerial snapshots. We plot two different densities/penetration rates, 84 vehicles per km^2/33% penetration rate and 255 vehicles per km^2/100% penetration rate. The partial penetration rate has been obtained by randomly selecting 1/3 of the vehicles as V2V-enabled. Fig. 3 clearly shows the impact of the buildings obstruction, with a substantial overlapping of the geometry of the wireless channel and that of the road network. Fig. 4 plots the average network connectivity as a function of density. Percolation is clearly observable somewhere between 50 and 100 veh/km^2.

Computing the path redundancy for all possible pairs is computationally very expensive, given the number of nodes used. We thus evaluate this path redundancy with relation to a single source point, that we strategically placed in the center of a major roundabout in the center of the city of Porto as depicted back in Fig. 2. This point could work as a road infrastructure Internet access point. We also limit our path redundancy analysis to the nodes within a distance of 1000m

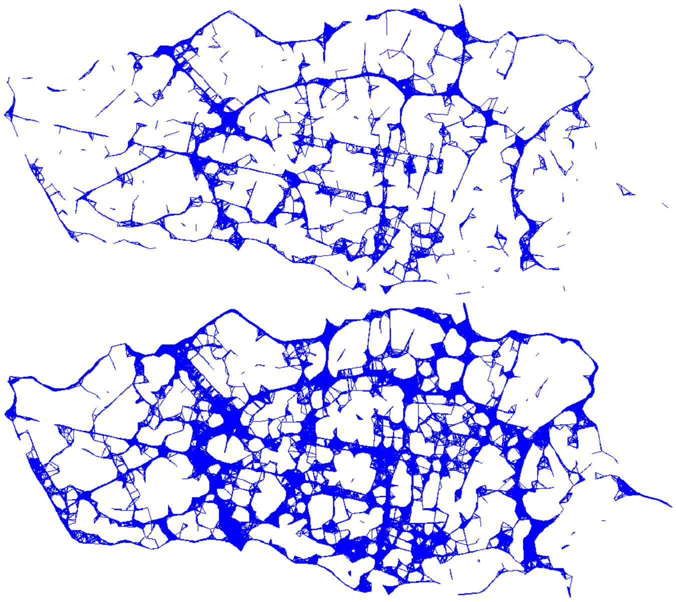

Fig. 3. Conn. graphs with varying densities 84 veh/km^2 and 255 veh/km^2

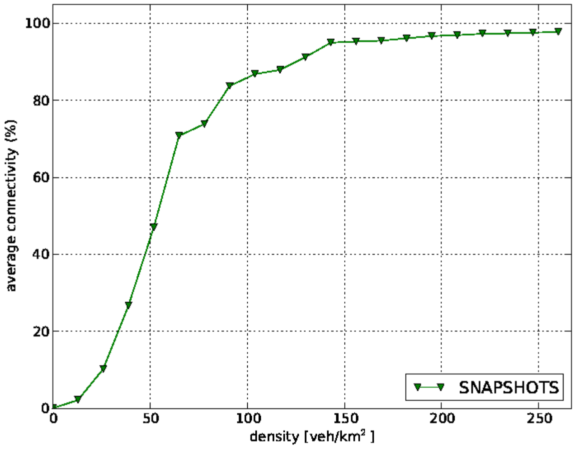

Fig. 4. Average network connectivity as a function of density

of this point. Fig. 5 plots path redundancy as a function of distance to the source point.

Our results report important differences compared to the literature based on less realistic mobility models, deriving, in particular, much higher values for path redundancy, which has an impact on the relevance of the broadcast storm problem.

III. CONCLUSION

In this paper we performed an urban connectivity analysis of a VANET through Stereoscopic Aerial Photography. Based on snapshots taken in an aerial survey over the city of Porto, we have computed the connectivity and path availability of 10,566 actual cars and trucks. Our results show significant differences compared to less realistic mobility models used for VANET connectivity analysis.

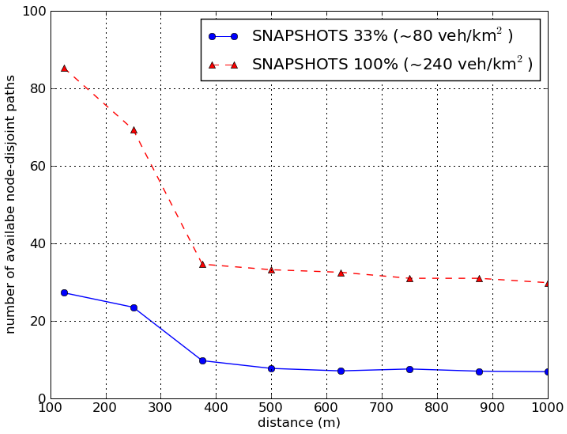

Fig. 5. Path redundancy as a function of distance to the source point (80 vehicles/km^2 and 240 vehicles/km^2)

REFERENCES

[1] N. Wisitpongphan, O. Tonguz, J. Parikh, P. Mudalige, F. Bai, and V. Sadekar, “Broadcast storm mitigation techniques in vehicular ad hoc networks,” *IEEE Wireless Communications*, vol. 14, no. 6, pp. 84–94, December 2007.

[2] T. Yamashita, K. Izumi, and K. Kurumatani, “Car navigation with route information sharing for improvement of traffic efficiency,” in *Intelligent Transportation Systems, 2004. Proceedings. The 7th International IEEE Conference on*, 2004, pp. 465–470.

[3] W. Viriyasitavat, O. Tonguz, and F. Bai, “Network Connectivity of VANETs in Urban Area,” in *IEEE SECON*, 2009.

[4] S. Kurkowski, T. Camp, and M. Colagrosso, “Manet simulation studies: the incredibles,” *Mobile Computing and Communications Review*, vol. 9, no. 4, pp. 50–61, 2005.

[5] O. Tonguz, W. Viriyasitavat, and F. Bai, “Modeling Urban Traffic: A Cellular Automata Approach,” *IEEE Communications Magazine, Special Issue on Automotive Network Series*, May 2009.