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Instantaneous multihop connectivity of one-dimensional vehicular ad hoc networks with general distributions of communication nodes

Wen-Long Jin[a,*], Wilfred W. Recker[b], Xiubin B. Wang[c,1]

[a] Department of Civil and Environmental Engineering, California Institute for Telecommunications and Information Technology, Institute of Transportation Studies, 4000 Anteater Instruction and Research Bldg, University of California, Irvine, CA 92697-3600, United States
[b] Department of Civil and Environmental Engineering, Institute of Transportation Studies, University of California, 522 Social Science Tower, Irvine, CA 92697, USA
[c] Zachry Department of Civil Engineering, Texas A&M University, College Station, TX, United States

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ABSTRACT

Connected and automated vehicle technologies hold great promises for improving the safety, efficiency, and environmental impacts of the transportation sector. In this study we are concerned with multihop connectivity of instantaneous vehicular one-dimensional ad hoc networks (VANETs) formed by connected vehicles along a communication path in a road network with given either vehicle locations or traffic densities, market penetration rates, and transmission ranges. We first define a new random variable for the location of the end node of a communication chain, which is a discrete random variable with given vehicle locations and a mixed random variable with given traffic densities. Then recursive, iterative, or differential equation models of instantaneous multihop connectivity between two communication nodes are derived from the relationships between end node probability mass or density function and connectivity. Assuming a simple communication model, the new models are applicable for general distribution patterns of vehicles and communication nodes, including non-evenly placed vehicles and nonhomogeneous Poisson distributions of nodes. With given vehicle locations, the computational cost for this new model is linear to the number of vehicles; with given traffic densities, we derive a new closed-form connectivity model for homogeneous Poisson distributions of communication nodes and an approximate closed-form model when distribution patterns of communication nodes are given by spatial renewal processes. We then apply the models to evaluate impacts on connectivity of traffic patterns, including shock waves, and road-side stations. The connectivity model could be helpful for designing routing protocols in VANETs and developing their applications in transportation systems.

* Corresponding author. Tel.: +949-824-1672; fax: +949-824-8385.
E-mail addresses: wjin@uci.edu (W.-L. Jin), wwrecker@uci.edu (W.W. Recker), bwang@civil.tamu.com, bwang@tamu.edu (X.B. Wang).
[1] Tel.: +979-845-9901.

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1. Introduction

Connected and automated vehicle technologies hold great promises for improving the safety, efficiency, and environmental impacts of the transportation sector (USDOT, 2015). In recent years, there has been much interest in vehicular ad hoc networks (VANETs) formed by connected vehicles in areas of wireless communications and Intelligent Transportation Systems (Blum et al., 2004). A corresponding communication protocol, IEEE 802.11p, has been developed to add wireless access in the vehicular environment (WAVE), with a transmission range up to 1000 m and delay in the order of 100 ms (Jiang and Delgrossi, 2008; Yao et al., 2013). In VANETs, inter-vehicle communications (IVC), including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, can be used to propagate time-critical and location-based traffic information. Due to their decentralized nature and low communication delay, IVC-based Advanced Traveler Information Systems have many advantages compared to centralized systems: (i) they can significantly improve safety, mobility, fuel efficiency, and other performance of the transportation system; (ii) they can enable many other location-based services; (iii) such decentralized systems are much more resilient to disruption, particularly in the event of natural or man-made disasters, when communications, management, and control are most needed; and (iv) the capital investment of such systems can be distributed to transportation agencies and individual drivers, and they can gradually evolve into full-fledged systems over time.

A fundamental performance measure of VANETs is multihop connectivity, which measures the probability for two communication nodes to be connected through multihop relays of messages. In the literature, there have been numerous studies of multihop connectivity of general radio networks, both one-dimensional (Cheng and Robertazzi, 1989; Piret, 1991) and two-dimensional (Desai and Manjunath, 2002; Gupta and Kumar, 1998; Philips et al., 1989). Research methodologies include theoretical analysis of asymptotic connectivity (Dousse et al., 2002) based on percolation theory (Gilbert, 1961; Meester and Roy, 1996) as well as Monte Carlo simulations (Tang et al., 2003). Performance measures used to evaluate connectivity include expected propagation distance (Cheng and Robertazzi, 1989), the probability for having at least one communication path between two nodes (Hartenstein et al., 2001), the *k*-connectivity (Bettstetter, 2002; Penrose, 1999), and the critical transmission range for asymptotic cases (Gupta and Kumar, 1998; Philips et al., 1989; Piret, 1991). In (Desai and Manjunath, 2002; Dousse et al., 2002), a closed-form solution of connectivity of one-dimensional network was presented. In addition, impacts of signal interferences on the connectivity of a wireless network was studied in (Dousse et al., 2005). In contrast, there are much fewer studies on the connectivity of VANETs specifically. In Hartenstein et al. (2001), the probability of establishing a communication path between two nodes was studied for simulated, bidirectional traffic. In Wu et al. (2004), an analytical model was proposed for estimating connectivity for vehicles following a Poisson distribution and moving randomly and independently. In Wu et al. (2005); Yang and Recker (2005), the propagation distance of information was studied using traffic simulations. In Miorandi and Altman (2006), the broadcast percolation distance was studied for one-dimensional wireless communication networks when the spacing between two consecutive vehicles is independent identically distributed (iid). In Schönhof et al. (2006), connectivity of VANETs was estimated subject to the mobility of vehicles, but the distribution of vehicles is assumed to be homogeneous. In Wang (2007), information propagation in instantaneous traffic was modeled as a Markov chain for vehicles following a Poisson distribution. In Ukkusuri and Du (2008), the geometric connectivity of one-dimensional IVC networks was studied for locations of vehicles following independent distributions, but with some disturbance. In Busson (2009), the information propagation process in VANETs was studied for a homogeneous distribution of communication nodes, but with a Frame Error Rate (FER) function in the distance. In Yin et al. (2013), an analytical model for multihop connectivity on two parallel roads was proposed with general independent distributions of vehicle headways.

We can see that, in most of existing studies, communication nodes are assumed to follow a homogeneous Poisson distribution. If all vehicles have the same probability to be equipped, this is equivalent to assuming that traffic density is the same along a communication path. However, in real road networks, this assumption is often violated, since traffic patterns on a road network are generally non-uniform (Jin and Recker, 2010; Saha and Johnson, 2004). There are many causes of non-uniform traffic patterns: (i) Different types of roads have different number of lanes and congestion levels; for example, freeways usually carry much higher traffic than local streets; (ii) On the same type of roads, e.g., on a freeway, traffic density is larger around bottlenecks caused by road geometry or accidents; (iii) Even on a homogeneous road, vehicle densities can vary dramatically at different times and locations, due to propagation of shock waves; and (iv) Signals and other control measures can create gaps among vehicle platoons. For example, Fig. 1 illustrates the traffic patterns in the Los Angeles freeway network during the morning peak period; we can see that traffic densities can substantially vary from location to location on the same road link. In Wisitpongphan et al. (2007), it was found that both inter-arrival times and inter-vehicle spacings follow negative exponential distributions with the NGSIM data for I-80 (FHWA, 2006). This would support the assumption of a spatially homogeneous Poisson distribution of vehicles. Note that, however, the data set only covers a homogeneous road section of less than half a mile, and traffic patterns were relatively stable during the study periods. In our study, with multihop information propagation along a long stretch of different types of roadways, it is more appropriate to relax the assumption.

In VANETs, messages can be relayed instantaneously or with delays. Delay-tolerant (or store-carry-forward) relays are helpful to improve the delivery ratio with low node densities, but communication delays in this mode can be too high for safety-related applications (Fall, 2003). In addition, with delay-tolerant relays, interactions between vehicle movements and information propagation can yield complex vehicular and information dynamics, and it is challenging to study performance of such a system (Kesting et al., 2010). In Du and Dao (2015), the information dissemination delay was modeled by