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Vehicle-to-vehicle connectivity on parallel roadways with large road separation

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ABSTRACT

This paper studies vehicle multihop connectivity of vehicular ad hoc networks (VANETs) on two parallel roads. It complements our earlier studies by considering a road separation distance larger than $\frac{\sqrt{3}}{2}L$ and considering signal blockage between roads, where L represents the transmission range. Assuming vehicles follow Poisson processes, we specifically derive exact formulas for the expectation, variance, and probability distribution of the information propagation distance. We further develop a closed form approximation for the expected distance. The analytical results are verified and compared with those from other headway distributions of varying coefficient of variation through Monte Carlo simulation.
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1. Introduction

The last decade has witnessed fast development of research on vehicular ad hoc networks (VANETs) largely because VANETs herald a significant potential to improve roadway traffic safety and efficiency (Ford Sync; BMW ConnectedDrive). The U.S. Department of Transportation (USDOT) has initiated the Connected Vehicles Program among other efforts in VANETs (Connected Vehicle Research). Vehcile connectivity is critical to VANETs efficiency, which depends to a great extent on roadway topological and geometric characteristics such as network connectivity and road spacing. Uncertain traffic flow, random vehicle location and mobility all add to the variations in vehicle connectivity on roadways.

Early studies on vehicle connectivity of VANETs generally resort to simulations (Yang and Recker, 2005; Tsugawa, 2002). Most analytical literature on vehicle connectivity so far only considers one road for technical maneuverability (Wang, 2007; Jin and Recker, 2010; Dousse et al., 2002; Ukkusuri and Du, 2008; Yousefi et al., 2008). The means of using one road to approximate the case of multiple roads or a network is coarse (Wang, 2007; Chen et al., 2010; Yin et al., 2013). Therefore, the recent years have seen research efforts to explicitly consider information propagation on parallel roadways. Wang et al. (2012) specifically study information propagation (an equivalent measure of vehicle connectivity) along parallel roadways when the roads are separated by a distance no larger than $\frac{\sqrt{3}L}{2}$, where L is the transmission range of a vehicle. These works show that it may lead to significant errors to approximate two parallel roads with a single one by virtually consolidating traffic onto one road. Following the same line of efforts, this paper complements Wang et al. (2012) by considering a road separation distance larger than $\frac{\sqrt{3}L}{2}$. It completes a full range of road separation distance. Clearly, the type of transmission region defined in the case in which the road separation is no larger than $\frac{\sqrt{3}}{2}L$ (see in Wang et al. (2012)) does not apply to

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Nomenclature

L	transmission range of vehicles
d	separation distance of road R_1 and R_2, satisfying $L \geqslant d \geqslant \frac{\sqrt{3}}{2}L$
λ_i	equipped vehicles densities on $R_i,\ i = 1,\ 2$
v	void distance
u	revisit distance
$d_i(v, u)$	expected propagation distance on $R_i,\ i = 1,\ 2$
$V_i(v, u)$	variance of propagation distance on $R_i,\ i = 1,\ 2$
h	equal to $2\sqrt{L^2 - d^2}$, a characteristic measure of road topology
$P_i(x, v, u)$	probability of propagation beyond a horizontal distance x starting with a vehicle
p_i	success probability of transmission from a vehicle on road R_i to the other road R_j, where $i \neq j$, when blockage between roads is present when both vehicles are within range of communication. $(1 - p_i)$ is the blockage probability in this case

our case of large road separation here because no parallelogram can be identified to be contained within a transmission range of a vehicle in our study problem. To be seen later, the transmission region in this paper, a critical concept for the modeling, is defined differently. Compared with the parallelogram defined as the transmission region in Wang et al. (2012), we identify an irregular shape inherent to the process of transmission to be defined as the transmission region. A unique feature in this case but not in the case of a shorter road separation distance is that vehicles within the propagation distance may be left out of communication because of 'holes' in the propagation distance. We propose formulas to estimate the number of vehicles left in the 'holes' and that outside of the 'holes'.

In this paper, we study connectivity by measuring instantaneous information propagation distance, i.e., the maximum horizontal distance to which a piece of information can propagate in a VANET on two parallel roadways. Instantaneity of information propagation is first argued in Jin and Recker (2010), and is later used in Wang et al. (2012). Analytically, this paper completes a full range of road separation distance together with earlier efforts. Practically, the roadway separation in this paper indicates a relatively sparse roadway network: roads are barely reachable within a transmission range, which takes place in rural or some urban areas. This study could serve as a springboard toward studying connectivity on grid networks. The layout of this paper follows that of Wang et al. (2012) by presenting exact models for the expectation, variance and probability of information propagation distance. An approximated closed-form expression for the expectation is also provided. A special feature of this paper is that it explicitly considers transmission failure due to signal blockage when transmitted between roads particularly because of obstructions within the large separation distance.

In what follows, we first define the study problem and transmission regions, and describe the transition process between regions in Section 2. Models for information propagation distance are developed in Section 3. We further give an approximation solution in Section 4. And numerical simulation is conducted in Section 5. We summarize the major findings in Section 6.

2. Definitions and problem statement

Consider two roadways R_1 and R_2 with a distance d apart where $\sqrt{3}L/2 \leqslant d \leqslant L$. Traffic densities on R_1 and R_2 are assumed to be λ_1 and λ_2, respectively. And vehicles on both roads follow Poisson processes. Vehicles have wireless communication with each other within an effective range L. We specifically consider instantaneous information propagation between vehicles as long as two vehicles are within L of each other. As a result, information is instantly propagated from vehicle A to vehicle B if they both communicate with vehicle C even if A and B are not within L of each other, so called multihop connectivity. When two vehicles are connected, they are considered to be in the same VANET. The objective of this paper is to characterize the longitudinal size of a VANET in a snapshot from a vehicle forward on the two roads.

To make the study general, we assume a failure probability, denoted by $1 - p_i$, where $i = 1, 2$, for within-range transmissions between the two roads due to buildings and other obstructions. As an example, a vehicle on road R_1 transmits a signal to a vehicle on R_2 within range L at a success probability p_1. In contrast, we assume no failure for within-range transmissions on the same road.

Note that the longitudinal size of a VANET from a particular vehicle forward also represents the maximum horizontal distance that information may be propagated in a direction each time. Because of randomness of vehicle presence on the roadway and because of vehicular mobility, VANETs may be considered as random graphs whose nodes are confined to locations on the roads. This paper is particularly interested in the random size of this graph. Note that the assumption of instantaneity implies no channel conflict and information latency, which appears to be a strong assumption. However, if one is able to characterize the probability of lost connectivity due to channel conflict, terrain changes, and other factors, this probability of loss may be multiplied to the vehicle presence probability to get an *adjusted* vehicle presence probability to use in the subsequent models of this paper.

As in Wang et al. (2012) and Yin et al. (2013), the process of information propagation is one of transitions between states, which requires a definition of transmission region and associated parameters. As in Fig. 1, we define the region *ABCD* as a