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Instantaneous communication throughputs of vehicular ad hoc networks

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A R T I C L E I N F O

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A B S T R A C T

Vehicular ad hoc networks (VANETs) formed by connected vehicles in a traffic stream could be applied to improve safety, mobility, and environmental impacts of a transportation system. In this paper, we present analytical models for the instantaneous communication throughputs of VANETs to measure the efficiency of information propagation under various traffic conditions at a time instant. In particular, we define broadcast and unicast communication throughputs by the wireless channel bandwith multiplied by the average probabilities that one vehicle is a successful receiver and sender in a VAENT, respectively. With a protocol communication model, we derive formulas to determine the probabilities for an equipped vehicle to be a successful broadcast receiver and a successful unicast receiver/sender, and obtain broadcast and unicast throughputs along discrete and continuous traffic streams. We further examine the impacts on communication throughputs of the transmission range and the interference range of dedicated short range communication devices as well as the market penetration rate of equipped vehicles and the percentage of senders. Finally, we investigate the influence of shock waves on communication throughputs.

1. Introduction

Inter-vehicle communications (IVC) among connected vehicles equipped with dedicated short range communication (DSRC) devices can be critical for the development of next-generation advanced transportation management systems (ATMS) and advanced traveler information systems (ATIS) (Aoki and Fujii, 1996; Yang and Recker, 2005; Grace et al., 2012), which can substantially improve safety, mobility, and environmental impacts of a transportation system (Luo and Hubaux, 2006; Sichitiu and Kihl, 2008). From a communication viewpoint, vehicles equipped with DSRC can form a vehicular ad hoc network (VANET) (Gorgorin et al., 2006), which are also known as "internet on road", CarTALK (Reichardt et al., 2002), and FLEETNET (Franz et al., 2001). In VANETs, equipped vehicles collect and share such traffic information as locations, speeds and acceleration rates so that drivers can make informed decisions on speeds, lanes, routes, departure times, destinations, modes, and other choices. Thus, VANETs can be used to leverage cooperative, vehicle-centric pervasive computing as a platform for transportation management and integrate a bundle of services supporting an arbitrary collection of transportation management applications (Recker et al., 2008).

VANETs have very distinct features from other wired or wireless communication networks, since (i) there is no energy constraint practically, as communication devices can be charged by car engines or batteries; (ii) the communication network

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topology is highly dynamic due to vehicle movements; (iii) vehicles usually have well-defined driving behaviors related to departure times, routes, lanes, and acceleration rates in a road network, and their locations in a road network are governed by road types and congestion patterns; and (iv) DSRC devices will penetrate the market gradually. Therefore, the distribution of equipped vehicles, i.e., communication nodes, in VANETs is random, dynamic, and nonhomogeneous.

In the literature, various aspects of VANETs have been studied. Communication reliability of single-hop communications was analyzed in Ma et al. (2011, 2012). For multi-hop communications, message routing algorithms subject to various levels of communication delay and reliability were studied in Li and Wang (2007) and Chen et al. (2010). Communication connectivity of VANETs has been well analyzed in Artimy et al. (2004) and Jin and Recker (2006). Particularly, in Jin and Recker (2006, 2010), connectivity of VANETs was proven to be related to the distribution of traffic densities, market penetration rate, and transmission range of DSRC devices.

In the last decade, many efforts have been devoted to analyzing communication throughputs and capacities in various wireless communication networks. Gupta and Kumar (2000) defined the per node throughput in a static wireless network with n randomly located nodes on a disc and a sphere, and the communication capacity could be achieved as much as $\Theta(\frac{1}{n\log n})$. Grossglauser and David (2002) proved that node mobility in a wireless network had potential in increasing the maximum throughput, i.e., capacity, dramatically. Li et al. (2001) investigated both throughput and capacity of a wireless ad hoc network via NS-2 simulation. In Yi et al. (2003) and Huang et al. (2007), a maximum flow formulation was constructed to estimate the improvement in communication capacities using directional antennas. Koskinen and Virtamo (2005) derived the probability of successful transmissions in a wireless multi-hop network with constant transmission power. In Du et al. (2009), the broadcast and unicast capacities of a VANET were defined as the maximum numbers of successful receivers and senders, respectively, and integer programming (IP) models were also proposed to calculate the capacities of a network. In the literature, however, most studies investigate communication capacities, i.e., the maximum values of throughputs, of general wireless ad hoc networks. These studies provide theoretical bounds of achievable throughputs, but fail to provide a reasonable estimation of throughputs under realistic conditions.

In contrast, we will study the expected communication throughput of a VANET, which measures the average efficiency of information transmissions in VANETs under realistic vehicular traffic conditions. Note that even though equipped vehicles can move as fast as 80 mph in VANETs, their displacements during each packet transmission time are rather small, in the order of 4 meters, since the DSRC transmission time is about 100 ms (Chen et al., 2010). Thus, we are concerned with one-hop communication throughputs of instantaneous VAENTs in this paper. We define the broadcast and unicast throughputs as the bandwidth of a wireless channel multiplied by the average probabilities that one vehicle is a successful receiver and sender in a VANET, respectively (Du et al., 2009). The relationship between throughputs and characteristics of traffic and wireless communication networks, such as vehicular distribution, market penetration rate (MPR) of equipped vehicles, transmission range, interference range, and the proportion of senders, is investigated. With a communication model of wireless signal fading and interference features, we develop analytical models to evaluate throughputs of VANETs along discrete and continuous traffic streams, for which the communication connectivity was studied in Jin and Recker (2009) and Jin and Wang (2010): in a discrete flow, individual vehicles' locations are known, and, in a continuous flow, traffic densities at different locations are given. We further study the impacts of shock waves on communication throughputs.

The rest of the paper is organized as follows. Section 2 introduces a protocol communication model and constructs a communication throughput model to estimate both broadcast and unicast throughputs. Section 3 and 4 theoretically derive the models for communication throughputs of VANETs along discrete and continuous traffic streams, respectively. Finally, Section 5 summarizes the contributions in this paper.

2. A communication model of information propagation

In the section, we consider information propagation along a discrete traffic stream of vehicles on a road. Suppose that there are n vehicles on the road, and their locations are denoted by x_i. If $i < j$, we say vehicle i is in the downstream of vehicle j, and $x_i \geqslant x_j$. Among these vehicles, $m = \mu n$ of them are IVC-equipped vehicles, where μ is the market penetration rate (MPR) of equipped vehicles. The set of equipped vehicles is denoted by $\mathcal{G}$. Refer to Table 1 for all notations used in this article.

2.1. A protocol communication model

Different from wired communication, wireless communication has two fundamental aspects: signal fading and interference (Tse and Viswanath, 2005). In this subsection, a protocol model of wireless communication presented by Gupta and Kumar (2000) is introduced to describe the necessary condition that a transmission is successfully received by an equipped vehicle over one hop subject to signal interference. This model is a simplification of a physical wireless communication model but still takes into account both signal interference and signal fading. For other types of wireless channel interference models, refer to Iyer et al. (2009).

In the protocol model, when vehicle i (the sender) transmits a message to vehicle j (the receiver), where $i, j \in \mathcal{G}, i \neq j$, the message is successfully received by vehicle j if and only if the following two conditions are satisfied: