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Optimization models to characterize the broadcast capacity of vehicular ad hoc networks

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ABSTRACT

Broadcast capacity of the entire network is one of the fundamental properties of vehicular ad hoc networks (VANETs). It measures how efficiently the information can be transmitted in the network and usually it is limited by the interference between the concurrent transmissions in the physical layer of the network. This study defines the broadcast capacity of vehicular ad hoc network as the maximum successful concurrent transmissions. In other words, we measure the maximum number of packets which can be transmitted in a VANET simultaneously, which characterizes how fast a new message such as a traffic incident can be transmitted in a VANET. Integer programming (IP) models are first developed to explore the maximum number of successful receiving nodes as well as the maximum number of transmitting nodes in a VANET. The models embed an traffic flow model in the optimization problem. Since IP model cannot be efficiently solved as the network size increases, this study develops a statistical model to predict the network capacity based on the significant parameters in the transportation and communication networks. MITSIMLab is used to generate the necessary traffic flow data. Response surface method and linear regression technologies are applied to build the statistical models. Thus, this paper brings together an array of tools to solve the broadcast capacity problem in VANETs. The proposed methodology provides an efficient approach to estimate the performance of a VANET in real-time, which will impact the efficacy of travel decision making.

1. Introduction

Vehicular ad hoc networks (VANETs) are infrastructure light vehicular networks, in which instrumented vehicles communicate with one another across wireless links directly or through possible intermediate vehicles. Different paradigms for information communication have been proposed under the umbrella of vehicle infrastructure integration (VII, 2007) by the USDOT: this includes vehicle to vehicle (V2V) communication systems such as VANETs; vehicle to infrastructure communication (V2I) and a hybrid mix of both V2V and V2I. The recent deployment projects have demonstrated the significant benefits of V2V and V2I systems on alleviating congestion, improving safety and in providing other non-traffic applications. Similarly, VANETs have a great potential to be applied to traffic control and traffic safety management so that the transportation system performance can be improved.

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There is a growing belief that the success of VANET-based inter-vehicle communications will facilitate a plethora of potential applications. In general, VANET applications will deliver functions and services in five key areas: (i) *traffic safety:* provides drivers with timely information to enable cooperative vehicle interactions with roadway environment to mitigate collision/injuries/deaths; (ii) *vehicular mobility and traffic operation:* increases road capacity by dynamic cooperative traffic operation and management; (iii) *consumer convenience:* provides information share for people sharing common interests; (iv) *vehicle probe data acquisitions:* aggregates real-time vehicular data for use in mobility and environmental applications; (v) *opportunistic data sharing:* provides opportunistic extension of the wireless mesh networks in improving the capacity and coverage, or information service for emergency situations. The first real 5.9 GHz dedicated short range communication technology (DSRC) was approved by FCC in December 2003 for vehicle infrastructure integration initiative (VII) applications in USA. Similarly, vehicle to vehicle communication for safety applications was tested in the advanced safety vehicle (ASV) program sponsored by the Japanese Ministry of Land, Infrastructure and Transport (MLIT) (ITS, 2008). Other projects in Europe such as NOW (2008) and FleetNet (2008) demonstrate the significant traffic management benefits that can be obtained by a meaningful integration of wireless communication and vehicular networks. VANET technologies, once successfully developed, will have significant impacts to the society in general.

The potential applications of VANETs have sparked a significant amount of research in both wireless communication and transportation areas. Although, VANETs have certain similarities to other mobile ad hoc networks, they are characterized by certain fundamental properties which makes their study more challenging (Blum et al., 2004; Moreno et al., 2005; Nekovee, 2007). For instance, VANETs are characterized by dynamic vehicular networks in which mobile nodes are varying both spatially and temporally. In addition, driver behavior, mobility constraints due to space and existing infrastructure and high speed/acceleration of vehicles cause unique challenges to solve these problems. Furthermore, the number of vehicles in a VANETs cannot be scheduled or controlled in real-time because drivers will enter or exit the traffic networks at different time instants. Several efforts have been invested on the performance of VANETs in the recent years. For example, Artimy et al. (2004, 2005a,b) studied the information propagation in VANETs by simulation of the transportation networks with an embedded communication network. Their simulation results show that the traffic factors, such as traffic density and traffic speed, affect the connectivity of VANETs significantly. Wu et al. (2004) studied the spatial information propagation in VANETs. Their analytical expression calculates the time delay of information transmission. Jin and Recker (2006) employed stochastic models to discuss the reliability of inter-vehicle communication under both uniform and general traffic streams. Assuming the presence of equipped vehicles follows an independent homogeneous Poisson process, Wang (2007) proposed a closed form expression for the expected propagation distance and its variance in the case of no transmission delay. Ukkusuri and Du (2008) explored the connectivity of a VANET at every time instant by integrating traffic flow features.

Recently, there is a great deal of interest in understanding the fundamental transmission capacity of wireless networks in which transmission is permitted only between single source–destination pairs. This is because this allows us to characterize the throughput of the wireless network which determines the efficiency and amount of information flow in the ad hoc wireless network. In a VANET, a related problem of characterizing is very important since the throughput of the information is dependent on the vehicular mobility and the opportunities available for communication. As in a self-organized system, each individual vehicle broadcasts its own messages to the entire network nodes without cooperation. Therefore, one of the primary problems for VANETs is data loss due to packet collision among concurrent transmissions (Jamieson and Balakrishnan, 2008). When the network loses data, retransmissions have to be conducted if the application requires a certain level of data fidelity, and doing so delay information propagation and degrade the information propagation efficiency. Therefore, the broadcast capacity acts as a key performance limit for information propagation efficiency in VANETs. Our *goal* in this paper is to understand this issue comprehensively using optimization approaches to characterize the efficiency of information flow in a VANET.

1.1. Related work

In the context of wireless ad hoc networks, there has been some related work which addresses the issue of network capacity. A seminal work is the research by Gupta and Kumar (2000) which defines per node throughput in a wireless network by a bit-distance product. This work supposes the network transports one bit-meter when one bit has been transported a distance of 1 m. The throughput of the network is measured by the number of bit-meters that are transported per second. Their results show that as a wireless network is formed by n identical randomly located nodes, each node capable of transmitting at W bits/s and with a fixed broadcast radius, the local throughput per node is $\Theta\left(\frac{W}{\sqrt{n\log n}}\right)$ bits/s under a non-interference protocol. It is also shown that if the distribution of nodes, the traffic patterns and the transmission range of each node are optimally chosen, the bit-meter product that can be transported by the network per second is $\Theta(\sqrt{An})$ bit-meters/s. Extending the case of stationary nodes in Gupta and Kumar (2000), Grossglauser and Tse (2002) study a mobile ad hoc network, in which n mobile nodes communicate in random source–destination pairs. Allowing the unbounded delay and using only the one-hop relaying, their results show the mobility of nodes increases per node throughput asymptotically as the number of nodes becomes arbitrary large. Studying a wireless ad hoc network with finite immobile nodes, Jain et al. (2005) propose methods to compute the upper and lower bounds of the network capacity with no power control. Behzad and Rubin (2006) propose that independent of nodal distribution and traffic pattern, the throughput capacity of an ad hoc wireless network is maximized by properly increasing the nodal transmission power. Gastpar and Vetterli (2002) extend