A Study on Information Throughput of Inter-vehicle Communications in a Unidirectional Traffic Stream

Zhe Wang, Wei Lu
Department of Automation
University of Science and Technology of China
Hefei, China 230027
zhew, michaell@mail.ustc.edu.cn

Wenlong Jin
Department of Civil and Environmental Engineering
University of California
Irvine, CA 92697
wjin@uci.edu, Corresponding author

Abstract

Inter-vehicle communications (IVC) based on mobile ad hoc networks have drawn increasing research interests in recent years. In this paper, we study throughput in an IVC system along a unidirectional traffic for different traffic conditions and transmission ranges of wireless units. Here, whether a vehicle is equipped or not is random, and the probability is assumed to be the market penetration rate. We first briefly introduce the communication performance measures and our simulation platform based on network simulator 2 and traffic flow theories. We then present Monte Carlo simulation results of communication performance measures for traffic flows of two congestion levels, information source and destination at different distances, and three transmission ranges. We compare our results with those obtained through simple connectivity analysis and find that the results are consistent for low connectivity, but the throughputs by ns-2 simulations are significantly lower than the theoretical results, due to packet losses caused by signal interferences. Together with further investigations, the study could be helpful for determining and designing appropriate communication hardware and software and intelligent transportation applications.

1 Introduction

Rapid developments in wireless communication technologies can well enable the development of inter-vehicle communication (IVC) systems, which can help to achieve safety, management, and other goals of transportation networks [14, 5, 23, 3, 30, 24]. The Federal Communication Commission (FCC) in 1999 allocated the spectrum from 5.850GHz to 5.925GHz for dedicated short range communications (DSRC) in ITS [4], which can be used for inter-vehicle communications, including vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Correspondingly, US Department of Transportation started nine ITS related initiatives in 2004, including Vehicle Infrastructure Integration (VII) [6]. In a VII system, vehicles equipped with communication units and road-side stations installed by transportation authorities can exchange information with each other. Such a communication system can be used to relay information of traffic conditions and transportation networks and could be helpful for improving safety and mobility of a transportation system. Compared with existing Advanced Transportation Information Systems, this distributed in formation system can develop gradually as internet with costs distributed to transportation authorities and users and is more resilient to disasters such as earthquakes.

Equipped vehicles in an IVC system can be considered as wireless communication nodes and form a vehicles' ad hoc networks (VANet), a special mobile ad hoc network (MANET). In a transportation network, mobile communication nodes have special mobility patterns: the density of vehicles can vary dramatically due to driving behaviors and restrictions of network geometry, and vehicles' positions are usually dependent on each other due to car-following and lane-changing rules. Such special mobility patterns can have significant impacts on the performance of VANets. Therefore, one can face many unique challenges when developing IVC systems [8]. For example, due to vehicles' accelerating, decelerating, merging, and diverging actions on the road, it is hard to maintain a stable multihop communication path between two nodes. This usually leads to no connectivity, low throughput, or long delay. In this sense, it is important to analyze various performance characteristics of an IVC system under different traffic situations, market penetration rates, and communication technologies.

There have been many studies on multihop connectivity in an IVC system in the literature [29, 15, 16, 17, 18, 28]. In these studies, the probability of establishing an instantaneous communication path is evaluated against traffic density, transmission range of wireless units, and market penetration rate of equipped vehicles. The study of multihop connectivity is essential for determining appropriate communication hardware and software under different application scenarios. In addition, as in other mobile ad hoc networks, information throughput and delay [26, 7, 27] are also fundamental performance measures of an IVC network. Theoretical analysis of capacity and throughput of mobile ad hoc networks have revealed that the share of per node capacity drops dramatically with the increase in the number of nodes [13]. This would have profound implication in the scalability of mobile ad hoc networks. For example, [21] suggests maintaining locality of information. However, it has also been argued that the long term per node capacity can be improved by taking advantage of mobility of nodes [10]. [19] studies the performances of IEEE 802.11 protocol in networks with strong mobility like vehicle networks. However, all vehicles are equipped. For an IVC system along a bi-directional four-lane roadway, the density of communication nodes can vary between 0 to 600 per km (with jam density of 150 veh/km), and the relative speed between two vehicles can be from 0 to 208 km/h (with free flow speed of 104 km/h). Therefore, it is of practical and theoretical interests to examine communication performance measures, such as throughput, in an IVC system for different traffic scenarios.

In this paper, we will study the throughput of a VANet along a uniform unidirectional traffic stream with the help of network simulator 2 (ns-2) [2]. This study is for understanding the fundamental properties of vehicles' ad hoc network under different traffic scenarios and is useful for designing the communication network and determining appropriate its applications. Here we consider the impacts of traffic density and transmission range of wireless units on throughput between two peers of different distances under different traffic scenarios. Here we assume a certain market penetration rate of equipped vehicles and whether a vehicle is equipped or not follows a Bernoulli distribution. In addition, we apply general MAC control and communication routing protocol provided by ns-2 and study throughput of a possible communication path between two nodes of different distances.

The rest of the paper is organized as follows. In section 2, we introduce traffic flow theories and basic principles of communication networks. Then, we describe mobility models and a Monte Carlo simulation model in section 3. In section 4, we carefully configure parameters in ns-2 and evaluate throughput along a unidirectional traffic stream for different transmission ranges and traffic densities. At last in section 5, we conclude our work.

2 Background

2.1 Traffic flow theories

Different from nodes in general mobile ad hoc networks, communication nodes in inter-vehicle communication networks are determined by drivers' departure time and route choice behaviors as well as car-following and lane-changing rules. That is, vehicles' trajectories are confined and can be predicted with help of traffic flow theories. For example, vehicles' trajectories can be calculated through macroscopic simulation with the LWR theory [22, 25]. The normal LWR model formula is

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0, \qquad (1)$$

where $q(x,t) = v(x,t)\rho(x,t)$, $\rho(x,t)$ is the density of a traffic flow, $v(x,t)$ is the speed of a traffic flow and $q(x,t)$ is the flow rate of a traffic flow.

Besides, the car following model is one of the classic microscopic traffic theories and can be used to compute vehicles' trajectories explicitly. The model is given by

$$\begin{cases} \frac{d^2}{dt^2}x_{i+1}(t+T) = \lambda \frac{d}{dt}S_i(t), \\ S_i(t) = x_i(t) - x_{i+1}(t), \end{cases} \qquad (2)$$

where $S_i(t)$ is the distance between two adjacent vehicles, and $x_i(t)$ is the position of vehicle i in the spacial coordinates and λ is the sensitive coefficient.

2.2 Definition of throughput

In communication networks, information throughput can be defined from different perspectives. In this study, information throughput of the logical communication path connecting a pair of information source and destinations is used as the measure. That is, for a node in ns-2, throughout can be computed by

$$T = \frac{\sum_i p_i}{t}, \qquad (3)$$

where i is sequence number of packet, t is the time of the last packet passed the node.

3 Simulation framework

3.1 Mobility models for network simulator 2

It is essential to capture the special mobility patterns of vehicles in a transportation network when simulating IVC with ns-2. In our simulations, mobile nodes' coordinates of starting positions and its future destinations can be obtained through observations, traffic flow theories, or traffic simulators. For a uniform traffic stream, in which vehicles are equidistantly apart from one another and have the same speed, the origin and destination of vehicle k ($k = 0, \cdots, K$) at $t = \tau$ can be simply computed as

$$x_k(0) = x_0 + k\Delta x,$$
$$x_k(\tau) = x_k(0) + v\tau,$$

where $x_k(t)$ is the position of vehicle k at time t, x_0 the position of vehicle 0 at $t = 0$, Δx the spacing between two consecutive vehicles, and v vehices' speed. Here $\Delta x = 1/\rho$, where ρ is the density of the uniform traffic stream. For a general traffic stream, in which vehicles' positions are obtained by observations or traffic simulators, vehicle k's starting positions and destinations during $[n\Delta t, (n+1)\Delta t]$ are $x_k(n\Delta t)$ and $x_k((n+1)\Delta t)$ respectively. Here Δt is the time step size for traffic simulations or observations. For examples, $\Delta t = \frac{1}{10}$ s or $\frac{1}{15}$ s in NGSim data sets [12], and $\Delta t = 0.2$ s in Paramics [9].

3.2 Monte Carlo simulation model

Different from [19], whether a vehicle is equipped or not is random in our study, and the probability for a vehicle to be equipped equals the market penetration rate μ. Therefore, the information propagation from a sender to a receiver in a traffic stream is a random process, and the average throughput at the receiver depends on the connectivity of the VANet as well as the interferences among transmissions. To evaluate throughput of a communication chain from an information source to an equipped vehicle at destination x, an idea is to carry out Monte Carlo simulations through repeated, random realizations of Bernoulli trials. Since in each Bernoulli trial, a communication chain is deterministic, its average throughput over successful communication connections would be an estimation of the corresponding throughput of an equipped vehicle at x.

Through observations, traffic flow theories, or traffic simulations, we can obtain the mobility patterns of $K + 1$ vehicles as $x_k(t)$. Then we carry out M Monte Carlo simulations as follows:

- Inputs for the experiments include market penetration rate μ, transmission range r, and the number of experiments M.
- In each experiment, $K + 1$ uniformly distributed random variables, among which random variable X_k corresponds to vehicle k ($k = 0, \cdots, K$), are generated in [0, 1]. If $X_k \leq \mu$, vehicle k is equipped, and we can obtain a realization of Bernoulli trials.
- For each Bernoulli trial, we provide trajectories of all equipped vehicles to ns-2 and simulate IVC from the sender. For experiment m, the throughput is denoted by T_i ($i = 1, ..., M$). Throughput is 0 kbps, if we cannot find a communication path from the sender to the receiver.

After finishing M experiments, throughput of an equipped vehicle at x can be computed by

$$T_M = \frac{\sum_i T_i}{M}. \tag{4}$$

To ensure the validity of Monte Carlo simulations, we need to choose a proper random number generators(RNGs) [20] who have a long period, good distribution properties, and a fast computing speed. In this study, random numbers are generated by a standard RNG in C-library realized by a linear congruential method [20] in the form of

$$x_{n+1} = (ax_n + b) \; mod \; m, \tag{5}$$

where a, b, and m are constants.

4 Simulation scenarios and results

4.1 Parameters configuration in ns-2

In this subsection, we configure parameters in ns-2 according to [19]. At the application layer, communication connections from an information source to an equipped vehicle at x are set up by constant bit rate (CBR) generators with packet size 230 bytes and inter-packet delay 0.02 s. For each Bernoulli trial, the ns-2 simulation time is 120 s. At the transport layer, UDP protocol is used for the study. At the network layer, Ad hoc On-Demand Distance Vector (AODV) routing protocol is selected for simulation. Note that, AODV is typically intended for use by MANETs, it offers quick adaptation to dynamic link conditions, low processing and memory overhead, low network utilization, and determines unicast routes to destinations within the ad hoc networks [1]. In this study, we only consider uniform traffic streams. Thus, for each Bernoulli trial, the communication topology does not change with time, and we expect that AODV to be the most efficient protocol for our study. At the MAC and the physical layer, IEEE 802.11 and the two-ray ground model are used for the study. Two-ray ground model is a radio-propagation model of the signal between two mobile nodes as one direct ray and a second ray reflected on the ground [11].

4.2 Simulation results in uniform traffic streams

In this subsection, we consider information propagation in a unidirectional, uniform traffic stream on a four-lane road-way, whose length is 50 km. Here traffic is sparse, and vehicles' travel speed is $125km/h$. The probability for vehicles to be equipped equals the market penetration rate $\mu = 10\%$. Traffic densities can be high at $\rho_1 = 14$ veh/km/lane or low at $\rho_2 = 5$ veh/km/lane. Vehicles run the same direction, and the length of the traffic stream is 10 km with the respective number of vehicles 560 and 200. Note that, in ns-2 simulations, we ignore the lateral distances between vehicles on different lanes and place all the vehicles on a line unidistantly; i.e., the traffic streams are equivalent to those with $\rho_1 = 56$ veh/km and $\rho_2 = 20$ veh/km on a single lane respectively, but vehicles are able to travel at the free flow speed.

We run Monte Carlo simulations for $M = 500$ times and study the average throughput performance of an equipped vehicle, whose distance from the sender is x ($x \in [0, 10]$ km), for different transmission ranges $r = 500$ m, 200 m, and 100 m.

Figure 1 and Figure 2 present the average throughputs of a receiver at different locations for two different densities. From the figures, we can see that the throughput increases with transmission ranges and traffic densities for multihop connections. For single-hop connections within transmission ranges, as expected, throughput is constant $100kbps$. In Figure 1, when the relative distance surpass 5.5 km, the throughput is lower than $10kbps$. Through ns-2 simulation results, low throughput results from no successful communication chains, no available route and no buffer space in interface queue. Due to these reasons, we can find that even

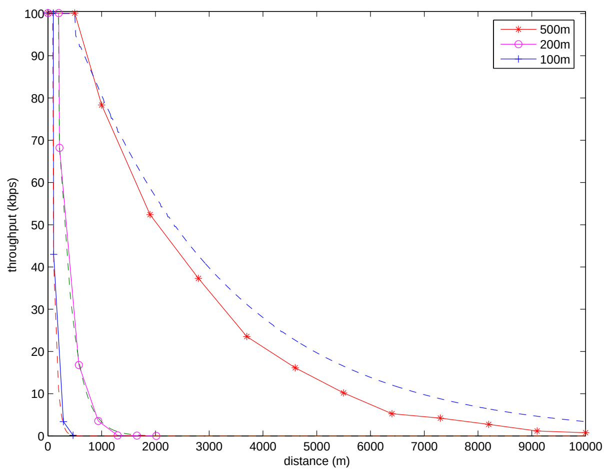

Figure 1. Average throughput of a receiver for different transmission ranges: total density $\rho_1 = 14 \times 4$ veh/km, $\mu = 10\%$, inter-packet delay $t = 0.02$ s, packet size 230 bytes. The corresponding dashed lines are theoretical values obtained from connectivity models.

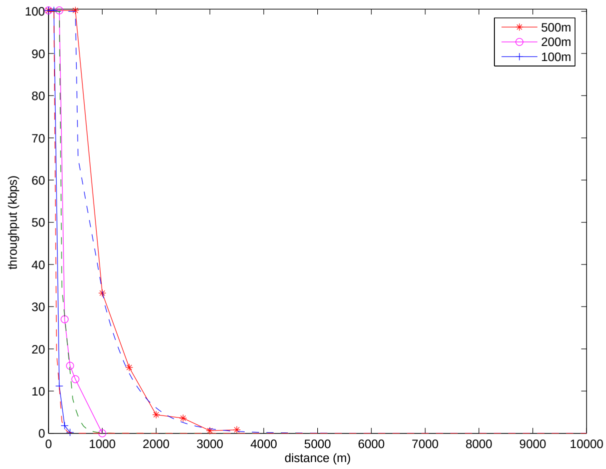

Figure 2. Average throughput of a receiver for different transmission ranges: total density $\rho_1 = 5 \times 4$ veh/km, $\mu = 10\%$, inter-packet delay $t = 0.02$ s, packet size 230 bytes. The corresponding dashed lines are theoretical values obtained from connectivity models.

information can't be transmitted further than $3.5km$ for transmission range $500m$ in Figure 2.

In the figures, the dashed lines are for theoretical values predicted by the connectivity between the sender and the receiver:

$$T(x, \mu, \rho, r) = T_0 \mathbf{c}(x, \mu, \rho, r), \quad (6)$$

where $T_0 = 100$ kbps is the throughput of the sender, x the distance between the receiver and the sender, r the transmission range, and the connectivity $\mathbf{c}(x, r, \mu)$ is obtained through connectivity models in [17]. With (6), we make the following two assumptions. First, the mobility of vehicles does not affect the connectivity or the throughput. Second, the throughput of the receiver is the same as that of the sender when the sender and the receiver are connected. That is, the model in (6) does not take into account of the impacts of vehicles' mobility on the connectivity or the throughput and packet losses caused by the interferences among several transmissions. We can see that the simulated results in throughput are quite consistent with those predicted by (6) in [17]. However, when the connectivity is relatively high for $\rho = 56$ veh/km and $r = 500$ m, we can observe significant difference between the ns-2 results and the theoretical results. By analyzing the trace data of ns-2 simulations, we find systematic packet losses after a number of hops in the AODV protocol, and the packet losses are caused by the interference between different transmissions. Such packet losses do not occur much in other scenarios, since the connectivity is so low that there hardly be two successful hops at the same time.

From the simulation results, we can see that the connectivity and, therefore, throughput can be enhanced by longer transmission range or denser traffic density. However, the increasing in connectivity can also increase the probability of signal interference and, therefore, decrease information throughput. Therefore, in inter-vehicle communications, the choice of transmission ranges is subject to constraints in traffic densities and the market penetration rates.

5 Conclusion and Future Work

In this paper, we attempted to study the impacts of the special mobility patterns of vehicles in a transportation network on the throughput performance of a VANet. Since whether a vehicle is equipped or not is random, we introduced a Monte Carlo simulation model for capturing the random effects. With ns-2, we simulated throughput performance of inter-vehicle communication in a unidirectional and uniform traffic stream with different transmission ranges and traffic densities. In particular, we compared our results with those predicted by the simple instantaneous connectivity models and found that the results are consistent for low connectivity, but the throughputs by ns-2 simulations are significantly lower than the theoretical results, due to packet losses caused by signal interferences. This simple study also reveals the trade-offs between improving the connectivity and the throughput: higher traffic densities, market penetration rates, or transmission ranges can improve the connectivity and the throughput of a VANet in a uniform traffic stream, but may cause more serious signal interferences among different transmissions.

This study is just a first step in our attempts to understand the performance of a VANet subject to the special mobility patterns of vehicles and the randomness in equipped vehicles. In the future, we will consider more complicated traffic scenarios, such as non-uniform and unidirectional traffic with a shock wave and bidirectional traffic, and higher transmitting rates of the sender. We will study the impacts of road-side stations and adopt position- and traffic-based routing protocols to better evaluate performances of inter-vehicle communication networks. We will also be interested in studying performance measures other than the connectivity and throughput, such as information propagation delay and jitter, which are also critical for determining and designing appropriate communication hardware and software and intelligent transportation applications.

Acknowledgement

This work was supported in part by National Natural Science Foundation of China (No. 50708107), Hi-Tech Research and Development Program of China (863 Project) (No. 2007AA11Z222), The open project of The Key Laboratory of Complex Systems and Intelligence Science at CASIA(20080105), National Basic Research Program of China (973 Project) (No. 2006CB705506), and the Science Research Fund of MOE-Microsoft Key Laboratory of Multimedia Computing and Communication (Grant No. 06120810). The views and results contained herein are the authors' alone and do not necessarily reflect those of the sponsors.

References

[1] AODV. http://www.ietf.org/rfc/rfc3561.txt.

[2] NS-2. http://www.isi.edu/nsnam/ns/.

[3] The FleetNet project. http://www.fleetnet.de.

[4] FCC allocates spectrum in 5.9 ghz range for Intelligent Transportation Systems uses. 1999. Accessed September 26, 2007.

[5] Safe and comfortable driving based upon inter-vehicle communication. http://www.cartalk2000.net/, 2000. Accessed November 11, 2003.

[6] Usdot's its program — major initiatives. 2004. Accessed January 30, 2007.

[7] N. Abramson. The Throughput of Packet Broadcasting Channels. *Communications, IEEE Transactions on [legacy, pre-1988]*, 25(1):117–128, 1977.

[8] J. J. Blum, A. Eskandarian, and L. J. Hoffman. Challenges of intervehicle ad hoc networks. *IEEE Transactions on ITS*, 5(4), December 2004.

[9] G. Cameron and G. Duncan. Paramics: parallel microscopic simulation of road traffic. *Journal of Supercomputing*, 10:25–53, 1996.

[10] S. Diggavi, M. Grossglauser, and D. Tse. Even one-dimensional mobility increases ad hoc wireless capacity. *Information Theory, 2002. Proceedings. 2002 IEEE International Symposium on*, 2002.

[11] N. Eude, B. Ducourthial, and M. Shawky. Enhancing ns-2 simulator for high mobility ad hoc networks in car-to-car communication context. *Proceedings of the 7th IFIP International Conference on Mobile and Wireless Communications Networks (MWCN 2005), Morocco, september*, 2005.

[12] FHWA. Next Generation SIMulation Fact Sheet. Technical report, December 2006. FHWA-HRT-06-135.

[13] P. Gupta and P. R. Kumar. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 46(2):388–404, March 2000.

[14] J. Hedrick, M. Tomizuka, and P. Varaiya. Control issues in automated highway systems. *IEEE Control Systems Magazine*, 14(6):21–32, 1994.

[15] W.-L. Jin and W. W. Recker. Instantaneous information propagation in a traffic stream through inter-vehicle communication. *Transportation Research Part B: Methodological*, 40(3):230–250, March 2006.

[16] W.-L. Jin and W. W. Recker. A monte carlo simulation model of inter-vehicle communication. *Transportation Research Record: Journal of the Transportation Research Board*, 2000:8–15, 2007.

[17] W.-L. Jin and W. W. Recker. An analytical model of multihop connectivity of inter-vehicle communication systems. Accepted, *IEEE Transactions on Wireless Communications*, 2008.

[18] W.-L. Jin and H.-J. Wang. Modeling Connectivity of Inter-Vehicle Communication Systems with Road-Side Stations. *The Open Transportation Journal*, 2:1–6, 2008.

[19] Y. Khaled, B. Ducourthial, and M. Shawky. IEEE 802.11 Performances for Inter-vehicle Communication Networks. *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*, 5.

[20] D. Knuth. The Art of Computer Progaramming: Seminumerical Algorithm. *volume 2. 3rd edition*, 1997.

[21] J. Li, C. Blake, D. De Couto, H. Lee, and R. Morris. Capacity of Ad Hoc wireless networks. *Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 61–69, 2001.

[22] M. J. Lighthill and G. B. Whitham. On kinematic waves: II. A theory of traffic flow on long crowded roads. *Proceedings of the Royal Society of London A*, 229(1178):317–345, 1955.

[23] R. Morris, J. Jannotti, F. Kaashoek, J. Li, and D. Decouto. CarNet: a scalable ad hoc wireless network system. *Proceedings of the 9th workshop on ACM SIGOPS European workshop: beyond the PC: new challenges for the operating system*, pages 61–65, 2000.

[24] W. W. Recker, W.-L. Jin, X. Yang, and J. Marca. Autonet: Inter-vehicle communication and network vehicular traffic. *International Journal of Vehicle Information and Communication Systems*, 2007. Forthcoming.

[25] P. I. Richards. Shock waves on the highway. *Operations Research*, 4:42–51, 1956.

[26] C. E. Shannon. A mathematical theory of communication. *The Bell System Technical Journal*, 27:379–423, 623–656, July, October 1948.

[27] A. Tanenbaum. *Computer Networks*. Prentice Hall PTR, 2002.

[28] X. Wang. Modeling the process of information relay through inter-vehicle communication. *Transportation Research Part B: Methodological*, 41(6):684–700, July 2007.

[29] X. Yang and W. W. Recker. Simulation studies of information propagation in a self-organizing distributed traffic information system. *Transportation Research Part C: Emerging Technologies*, 13(5-6):370–390, 2005.

[30] A. K. Ziliaskopoulos and J. Zhang. A zero public infrastructure vehicle based traffic information system. In *TRB 2003 Annual Meeting CD-ROM*, Washington, D.C., 2003.