AN EMPIRICAL STUDY OF INTER-VEHICLE COMMUNICATION PERFORMANCE USING NS-2

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ABSTRACT

In recent years, there has been increasing interest in inter-vehicle communications (IVC) based on wireless networks to collect and distribute traffic information in various Intelligent Transportation Systems applications. In this paper, we study the performance of IVC under various traffic and communication conditions by means of simulation analysis. We consider impacts of shock waves, transportation network, traffic densities, transmission ranges, and multiple information sources. We used a state-of-the-art communication network simulator ns-2 to measure *success rate* and *message delivery ratio* (MDR) for flooding-based IVC communication. For reasonable realism in the deployment scenario, we assume that only a partial set of vehicles on the road are equipped with communication devices, according to the market penetration rate. A Monte-Carlo simulation method is used with repeated random sampling of IVC-equipped vehicles. The results indicate how these parameters can impact the performance of IVC communications. By comparing the flooding-based approach (theoretical and simulation) and simulation results using AODV (Ad Hoc On-Demand Distance Vector), we conclude the importance of traffic environment and network protocol for IVC communication.

INTRODUCTION

With increasing availability of wireless communication devices, IVC is an emerging technology that can help vehicles share or propagate useful information for drivers for traffic congestion mitigation, safety warning, and traffic management. The Federal Communication Commission (FCC) of USA has allocated a spectrum of 75 MHz in 5.9 GHz range for Dedicated Short Range Communications (DSRC) (*1*). To develop Intelligent Transportation Systems strategies based on DSRC and other wireless communication technologies, the US Department of Transportation started the Vehicle Infrastructure Integration (VII) initiative among eight others (USDOT, 2004). In a VII system, vehicles equipped with communication units and road-side stations installed by transportation authorities are able to exchange information with each other through inter-vehicle communication, including vehicle-to-vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications.

As early as in the 1990s, IVC has been used to help drivers respond more promptly to emergencies on a road in the California PATH automatic highway project (*2*). The Autonet project at University of California, Irvine developed concepts for IVC in the late 90s, which were further studied in a National Science Foundation Project from 2003 (*3*). In 2002, the CarTalk project in Europe studied Advanced Driver Assistance Systems based on IVC (*4*). In recent years, various stakeholders have come together to address these short-term and long-term challenges and initiative efforts have been formed, such as the Europe eSafety and US IntelliDrive programs.

Every year, millions of traffic accidents occur worldwide with forty thousand fatalities in US and Europe alike. A central theme for transportation planners is focused on increasing road safety. The European Transport Policy set the goal to reduce road fatalities by 50% by the year 2010 *(5).* Furthermore, US DOT's Research and Innovative Technology Administration (RITA) has challenged the industry to reduce traffic crashes by 90% by 2030 *(6)*. As a result, safety related applications with localized information exchange have been an important driving force for the development of IVC. Since the concept of Carnet (*7*) and the project of Fleetnet (*8*) were introduced in 2000, an IVC system has been studied as a special case of mobile ad hoc networks (MANET) and termed as vehicular ad hoc networks (VANET). Thus, an IVC network could develop into a vehicular network (car to car communication) or

"Internet on the road" (*8*), a possible venue for publishing advertisement and infotainment information.

In an IVC network, communication nodes, i.e., vehicles equipped with communication units, usually move at high speeds and are constantly entering and leaving roadway segments. In transportation networks, the density of vehicles can vary dramatically due to driving behaviors and restrictions in the network geometry. The network topologies for IVC are highly dynamic (*9*, *10*). The performance of IVC is affected by the underlying transportation network structure and vehicular traffic dynamics as well as the wireless device and communication protocols.

There are various performance measures to analyze the effectiveness of communication protocols which include: connectivity, capacity, throughput, delivery ratio, end-to-end delay, and packet reception rate. In our study, we evaluate the performance of IVC by measuring the probability of successful information propagation and MDR in uniform and shockwave traffic streams in unidirectional roads (one-dimension) and uniform traffic for bi-directional roads (two-dimension). We use uniform traffic to compare our simulation results with a theoretical model and for consistency in the speed-density relationship. We consider the impact of density, transmission range, routing protocol, market penetration rate of equipped vehicles, and number of information sources on success rate and MDR. We define success rate as a probability of success for information to travel beyond a certain location and MDR as the percentage of data packets received by the receiver from those transmitted by the information source.

In many studies, communication nodes are assumed to follow a spatial Poisson distribution on a plane or to move randomly in a given area. However, in real traffic the movement and positions of vehicles are not independent of each other. The aim of this study is to understand the fundamental properties of IVC under different traffic and communication scenarios. Since we assume a certain level of market penetration rate of equipped vehicles, the Monte Carlo method that randomly selects equipped vehicles via Bernoulli trials is used. For network simulation, we use *ns-2* (*11*) with realistic communication protocol stack based on IEEE 802.11 Medium Access Control with the information propagated based on a flooding scheme.

RELATED WORK

The fundamental performance measures in mobile ad hoc networks include multi-hop connectivity, information throughput and communication delay (*12*, *13*, *14*). Theoretical analyses of capacity and throughput of mobile ad hoc networks have revealed that per-node capacity drops dramatically with the increase in the number of nodes (*15*). This has profound implications on the scalability of MANETs. Through theoretical (*16*, *17*, *18*, *19*), simulation-based (*20*, *21*), and field studies (*22*), it has been observed that multi-hop connectivity of an IVC system is highly related to the distribution of vehicles on a road, transmission range of wireless units, and market penetration rate of equipped vehicles.

As routing protocols in wireless multi-hop ad hoc networks can significantly influence communication reliability and reachability (*23*), various types of routing protocols such as unicast, multicast, and broadcast have been studied to evaluate the feasibility and performances of ad hoc network on rectangular areas with random waypoint mobility (*24*, *25*). *Wang et al*. (*26*) studied information throughput of inter-vehicle communication in a unidirectional uniform traffic stream using AODV (*27*). Similarly, it is necessary to investigate how information propagation in an IVC network is affected by vehicular traffic dynamics.

The rest of the paper is organized as follows. First we introduce success rate and message delivery ratio as the performance measure of our study. Then, we describe our simulation environment and evaluate different mobility patterns and communication scenarios. We conclude with insights on the impact of traffic dynamics and network parameters in the performance of an IVC system.

SIMULATION ENVIRONMENT

THEORETICAL MODEL

We first assume that whether a vehicle is equipped with communication capability or not is a random occurrence based on a simple market penetration ratio, μ and if node i and j are within transmission range *r*, the probability of propagating information is set to 1. Therefore, the information propagation from sender to receiver in a traffic stream is a random process, and the throughput and message delivery ratio at the receiver depends on the connectivity between the sender and the receiver. We denote *the end node probability* for vehicle k to be the end of a communication chain starting from sender m by $\mathrm{P}(m,k)$ and the probability for information to propagate from node m to node k by $\mathrm{c}(m,k)$. $\mathrm{c}(m,k)$ is independent of vehicles outside $[x(m),x(k)]$, where $x(m)$ and $x(k)$ indicate vehicle location. $u(k)$ and $d(k)$ are defined as *upstream reach* and *downstream reach* as the farthest vehicle within its transmission range r from vehicle k. Finally, given vehicle positions distributed according to uniform or general traffic, the recursive model of multi-hop connectivity can be written as

$$\mathrm{P}(m,k) = \mathrm{c}(m,k)\mu(k)\prod_{j=k+1}^{d(k)}\left(1-\mu(j)\right),$$

where, $\mathrm{c}(m,k) = 1-\sum_{i=m}^{u(k)-1}\mathrm{P}(m,i)$

$$u(k) = \min\{i|x(k)-x(i) \le r, x(i) \in [x(m),x(n)]\}$$

$$d(k) = \max\{i|x(i)-x(k) \le r, x(i) \in [x(m),x(n)]\}$$

Further details of the model can be seen in (*28*).

PERFORMANCE MEASURES

We measure *success rate* and *message delivery ratio* from an IVC equipped information source at location x using the Monte-Carlo method with randomly repeated simulation by Bernoulli trials, which is similar to (*26*). For the Monte-Carlo simulation, we generate the mobility patterns of K vehicles as $x_k(t)$ and carry out M randomly repeated simulations. In each experiment, we have K independent variables ($X_k,\ k=0,\dots,K$) which correspond to vehicles on a given traffic stream. For the Bernoulli trials, we generate a random number in [0,1] and if $X_k \le \mu$, vehicle k is IVC equipped.

For the measurement of *success rate*, we set the most upstream vehicle as an information source in uniform traffic, while in shockwave traffic scenario an information source is set at the mid-point of two traffic streams with varying densities. The following notations describe the *success rate* after M experiments:

- D_i: Information propagation distance in the i_{th} simulation ($i = 0, \ldots, M$)
- $I_i(x)$: Indicator function for message reception at location x in the i_{th} simulation

$$I_i(x) = \begin{cases} 1 & if\ x \leq D_i \\ 0 & if\ x > D_i \end{cases}$$

- $S(x)$: Success rate at location x

$$S(x) = \frac{\sum_{i=0}^{M} I_i(x)}{M}, (0 \leq S(x) \leq 1)$$

The *message delivery ratio* is defined as the number of received data packets by the receiver divided by the number of transmitted packet by the sender. In flooding, an information source transmits a message to all neighbors within its transmission range. Subsequently, the nearby nodes then transmit the message to their neighbors and finally the message is propagated to all nodes in network. Although the flooding based approach incurs some unnecessary overhead and inefficiencies, it can quickly disseminate useful information for emergency information propagation and does not require any routing table maintenance or update in the communication design. The following notations describe the *message delivery ratio* in the experiments:

- T^k: Total number of data packets transmitted by a source k
- R_i^k: Total number of data packets received at a receiver i from a source k
- $MDR^k(i)$: Message Delivery Ratio at a vehicle i from a source k

$$MDR^k(i) = \frac{R_i^k}{T^k}$$

MOBILITY MODELS

We consider two mobility models, uniform traffic and shockwave traffic. For the speed-density relationship, we use the well-known triangular fundamental diagram (*29*, *30*).

$$V(\rho) = \begin{cases} v_f, & 0 \leq \rho \leq \rho_c \\ \frac{\rho_c}{\rho_j - \rho_c}\frac{\rho_j - \rho}{\rho} v_f, & \rho_c \leq \rho \leq \rho_j \end{cases}$$

where v_f=104 km/h, ρ_j=150 veh/km/lane, and $\rho_c = 0.2\rho_j = 30$ veh/km/lane

In uniform traffic, the spacing between vehicles are the same and vehicles travel at the same speed. The shockwave scenario is created by two traffic streams with varying densities (hence, different speeds according to the triangular relationship) that meet on a unidirectional road.

SIMULATION FRAMEWORK

We use the network simulator *ns*-2, an open-source object-oriented discrete event simulator. The *ns*-2 tool is the most common tool used by computer networking researchers. According to a survey conducted in 2005, *ns*-2 is the simulator of choice used by 43% of all published ACM research papers related to mobile ad hoc networks (*31*). Though it is a communication network simulator, *ns*-2 itself have some supporting tools for mobility modeling (e.g. random waypoint, Manhattan model) and cannot simulate vehicular dynamics. The generation and movement of vehicles in our work follow theoretical traffic models and are then converted and feed into *ns*-2. Finer details of traffic such as lane changing and car-following were assumed to be not critical for this study.

When a simulation is complete, *ns*-2 generates a trace (*.tr) text file which is then analyzed using a scripting language such as perl and awk. Since every scenario must be simulated repeatedly, we build a Monte-Carlo simulation framework, nsHelper, written in C++. Figure 1 illustrates the sequence of steps in the simulation framework and how the custom-build 2Helper tool facilitates the Monte-Carlo method and the mobility generation, data collection, and gathering of statistics related to the performance measures. A sample screenshot of the visualization output produced by *ns*-2 is shown in Figure 2 for a two-dimensional arterial network with 16 intersections.

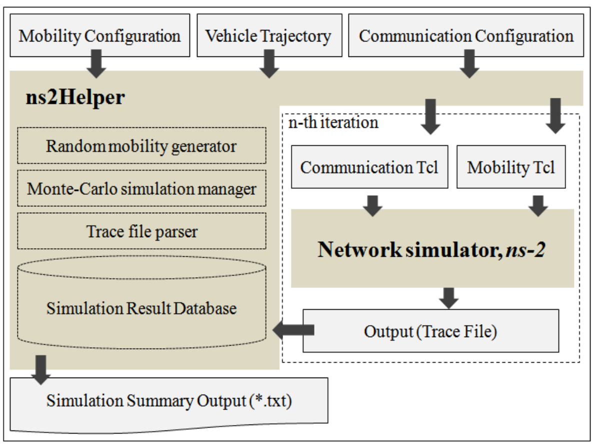


Figure 1. Simulation Framework

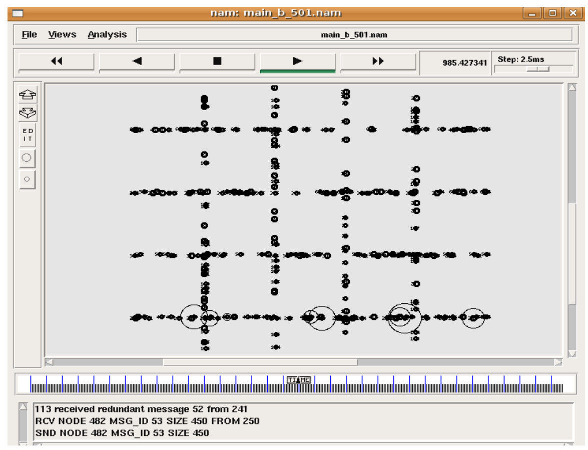


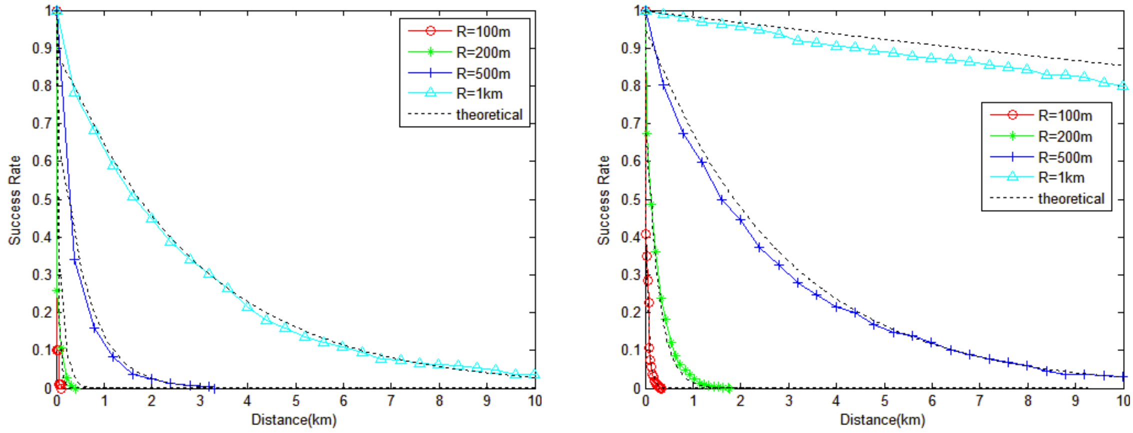
Figure 2. *ns*-2 simulation

SUCCESS RATE

In this section, we investigate the *success rate* for both uniform traffic and shockwave traffic by setting one vehicle as an information source, which transmits a single message of 230 bytes and measuring how far the message travels along the traffic stream.

UNIFORM TRAFFIC

For uniform traffic, we simulate unidirectional uniform traffic stream moving in the same direction with four lanes along a 20 km highway stretch. We set the information source at the most upstream point. For four lanes, the traffic densities are ρ_1 = 20 veh/km and ρ_2 = 56 veh/km, which has 800 and 1200 vehicles traveling at free flow speed (v_f = 104 km/h). We use the Monte-Carlo method (M = 500 times) with different transmission ranges R = 0.1, 0.2, 0.5, and 1km with 10% market penetration rate (μ = 0.1) of randomly IVC-equipped vehicles in the simulation.



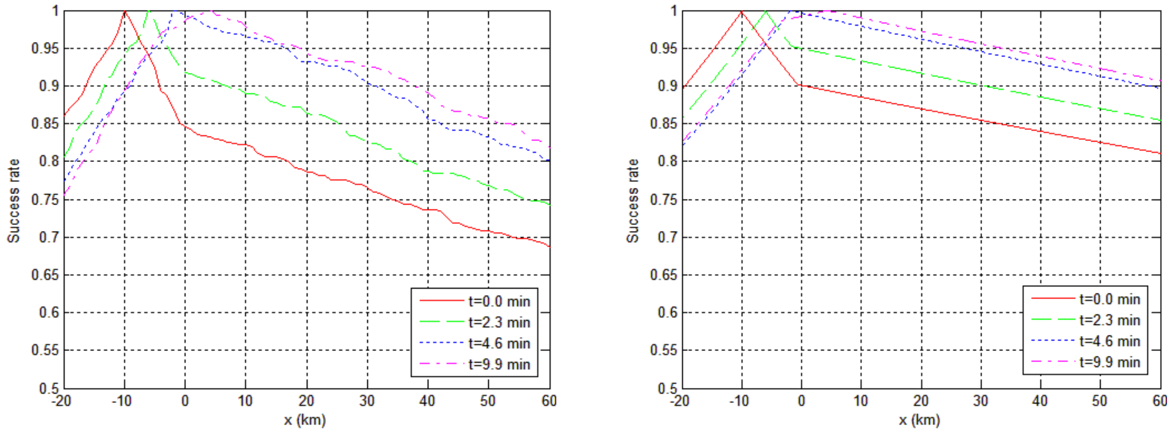
3(a) ρ_1 = 20 veh/km **3(b) ρ_2 = 56 veh/km**

Figure 3. Success Rate with Uniform Traffic Steam

Figure 3 shows the success rate of a receiver at different locations x ($x \in [0,10]$ km) from the sender located at distance 0. The dashed lines indicate theoretical values from the analytical model in (*15*). First, we see that the simulation results are consistent with the analytical model and as the distance from the information source increases, the success rate decreases. Communication performance is strongly affected by vehicle density and transmission range. In Figure 3(a), when R = 500m, the success rate at 3 km is almost zero, while the success rate at 3 km is more than 0.3 and the message travels more than 10 km according to Figure 3(b). When the transmission range is low (i.e. 100 or 200 meters), information cannot propagate more than 1 km. As the message propagation in IVC is multi-hop over multiple vehicles, shorter transmission range and low traffic density negatively affects the travel distance in the traffic stream.

SHOCKWAVE TRAFFIC

In this section, we examine success rate in shockwave traffic scenarios. Initially, we assume that we have capacity flow with ρ_u = 30 veh/km/lane for upstream to x = 0 and congested flow ρ_d = 40 veh/km/lane for downstream. Using the speed-density relationship described earlier, the corresponding speeds v_u = 104 km/h and v_d = 71.5 km/h are derived respectively. At time t = 0, a shockwave is created and moves backward at speed v_s = -26 km/h. In the simulation, we assume the traffic stream length to be more than 80 km with market penetration rate 10 % (μ = 0.1) and transmission range R = 1 km. To simulate shockwave traffic, we set information source at x = -10 km in the capacity flow, density ρ_u = 30 veh/km/lane and speed v_u = 104 km/h.



4(a) Flooding **4(b) Theoretical**

Figure 4. Success Rate with Shockwave Traffic Stream

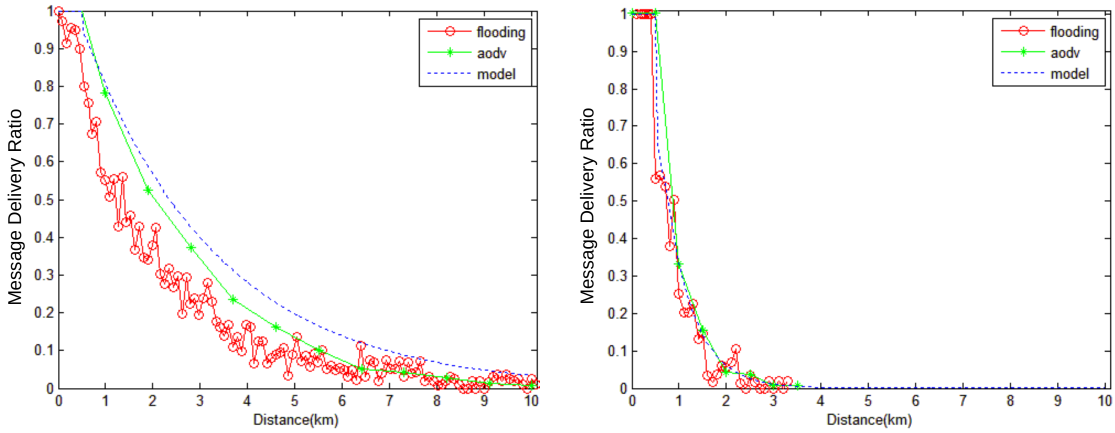
Figure 4 shows the success rates in both forward and backward directions at four instants of time: t_0 = 0, t_1 = 2.3, t_2 = 4.6, and t_3 = 9.9 minutes. In the simulation, the corresponding locations of information source are -10 km, -6 km, -2 km, and 4.3 km, and the locations of shockwaves are 0 km, -1 km, -2 km, and -4.3 km. We observe that success rate is symmetric with respect to information source within the same traffic density. However, it is clear that success rate depends on traffic density and changes dramatically when meeting a different traffic density. Comparing Figure 4(a) with 4(b), we see that the analytical and simulation results are similar initially, but are significantly different as the distance from the information source increases. For example, at location 60 km, the difference in success rates for the case of t_0 = 0 is more than 10%. This is attributed to the wireless communication signal interference in the simulation due to nodes re-broadcasting unheard messages while the theoretical model assumes guaranteed message delivery within transmission range. Further, the theoretical model assumes that messages are directly delivered to the farthest IVC-equipped vehicle (most forward within range) to minimize the hop count.

MESSAGE DELIVERY RATIO

In this section, we evaluate the performance of inter-vehicle communication by measuring the message delivery ratio for vehicular network in different traffic densities, number of information sources, and two-dimensional road layouts. We set the communication bandwidth to 1 Mbps and information source that transmits packets at periodic intervals (0.02 sec) with a fixed packet size (230 bytes/packet) in the simulation time period, which is a CBR application in (*32)* over M = 500 simulation runs with varying IVC-enabled vehicle locations based on the market penetration rate (μ = 0.1).

IMPACT OF ROUTING PROTOCOL

In this experiment, a single information source is set and follows the same communication scenario as (*26*) to compare our flooding-based method with AODV. AODV is a popular on-demand routing protocol to deliver messages in MANETs.



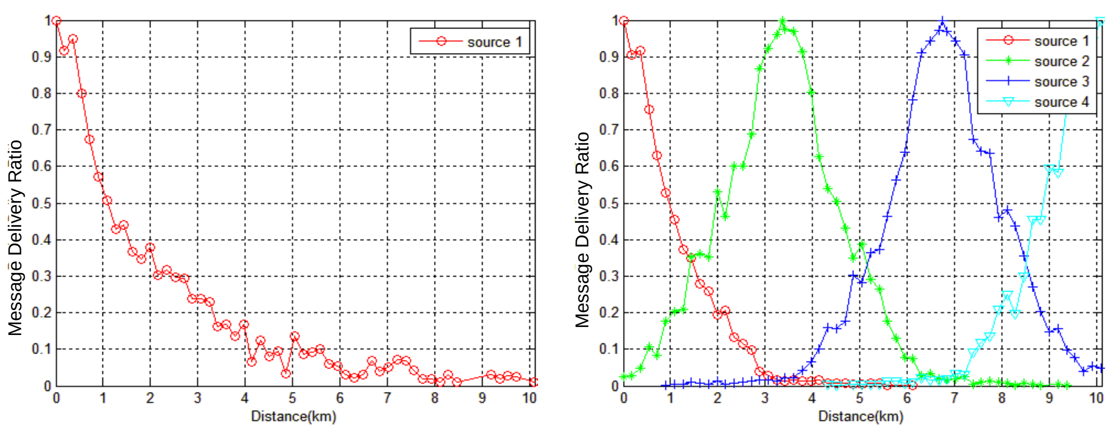
5(a) ρ_1 = 56 veh/km **5(b) ρ_2 = 20 veh/km**

Figure 5. Message Delivery Ratio with *R* = 500 m, μ = 0.1

Figure 5 presents message delivery ratio for two different traffic densities. Similar to success rate, the message delivery ratio also decreases as the distance from the information source increases. For low traffic density, there is no significant difference between flooding, AODV, and theoretical model as shown in Figure 5(b). However, in high traffic density, Figure 5(a), degradation of the flooding method is evident in comparison with the other methods caused by the broadcast storm problem where redundant broadcasts cause wireless radio contention and collision problems. Further, AODV performed better than the flooding method as AODV establishes a shortest-path-based routing scheme (routing table construct) and then disseminate messages in the MANET. Consequently, we can see that the choice of routing protocols can exhibit different performance measures for the same mobility scenario and transmission range.

IMPACT OF MULTIPLE INFORMATION SOURCES

This experiment evaluates the overall communication performance when multiple vehicles are sending messages simultaneously. We place multiple information sources (up to a maximum of four) equally distributed over the same traffic scenario with Figure 5(a) and measure the message delivery ratio. Figure 6 compares two different cases, single and four information sources. From Figures 6(a) and 6(b), we see the impact of communication traffic on delivery distance when multiple information sources are present in the network.

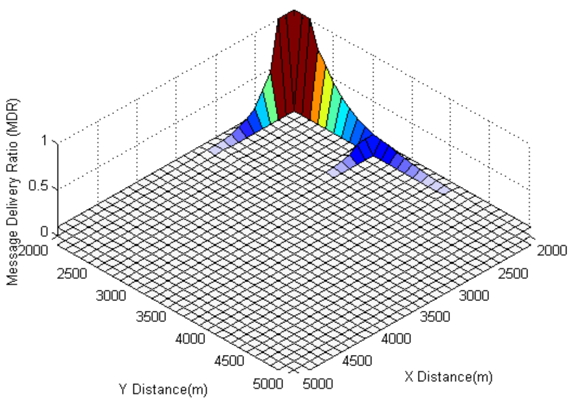


6(a) Single Information Source **6(b) Four Information Sources**

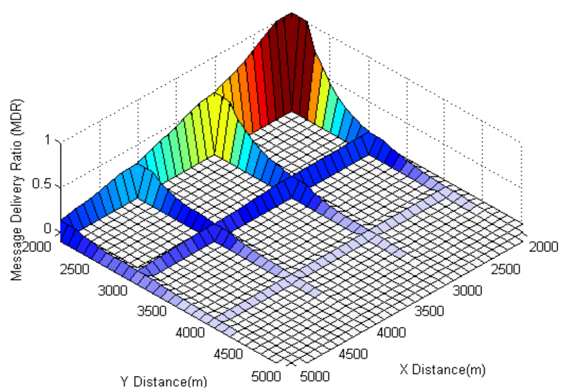
Figure 6. Message Delivery Ratio with Multiple Sources with *R* = 500 m, μ = 0.1

IMPACT OF TWO DIMENSIONAL NETWORKS

In this section, we construct a two-dimensional network (5 km x 5 km) with traffic flow in both forward and opposite directions for uniform traffic to better understand communication performance in the intersection junction of arterial road. A fixed value of R = 250 m is used based on the flooding communication scheme. We designate the four longitudinal traffic flows to 30 veh/km and vary the four latitudinal traffic flows (x-axis) with 15 veh/km and 60 veh/km in separate experiments. In Figure 7, we observe that with a 10% MPR, a density of 15 veh/km can only propagate 1 km which covers up to 3 intersections in 7(a) and 60 veh/km 5 km which covers up to 12 intersections in 7(b). This is due, in part that as traffic flow meets at the intersection information can be propagated further as the two traffic streams meet. Hence, Figure 7(b) shows significant gains in message distance traveled by doubling the traffic density.



7(a) ρ_x= 15 veh/km and ρ_y = 30 veh/km



7(b) ρ_x = 60 veh/km and ρ_y = 30 veh/km

Figure 7. Two Dimensional Road Network

CONCLUSION

In this paper, we investigate and illustrate the impact of traffic stream and wireless communication on the performance of IVC. We develop a simulation framework with *ns*-2 that generates different combinations of communication and mobility scenarios and use the Monte-Carlo method to evaluate system wide performances. For the system performance of IVC, we consider *success rate* and *message delivery ratio*. The result shows that traffic density, transmission range, and number of simultaneous transmitters are major contributing factors on the communication performance. In shockwave traffic scenarios, the success rate changes dramatically when it meets a different traffic density. By comparing it with analytical model, simulation results are lower than theoretical values due to signal interference and inefficiency of the flooding method. Then, we study *message delivery ratio* for different traffic densities, transmission ranges, multiple information sources, and two dimensional road layouts. We conclude that higher traffic densities and longer transmission range can cause greater interferences that lead to more packet drops. Both traffic and network can significantly impact the performance in inter-vehicle communication.

Systematic consideration of the requirements and constraints imposed by applications, communication, and vehicular traffic flow are necessary for communication routing protocol design. For example, a mobility model can describe information on vehicle headways, which is useful since vehicles need to be within transmission range to communicate. For future research, we plan to extend our simulation framework to complex traffic scenarios using microscopic traffic simulator such as PARAMICS. However, a joint approach involving both network and traffic simulator can create greater challenges such as time-synchronization between the two simulators and ensuring compatibility. Our future plans include measuring the performance of IVC for bidirectional directions and delay-tolerant network schemes where vehicles "store-carry-forward" messages (*33*). These issues, along with other improvements at the lower levels of the communication protocol stack, will be important future research questions related to the design of reliable, scalable, and efficient routing protocols for vehicular networks.

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