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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 the probability of success (*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 in determining the MDR for IVC communication.

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INTRODUCTION

With increasing availability of wireless communication devices, Inter-Vehicle Communications (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 (ITS) 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.

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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.

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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 packet delivery ratio 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 message delivery ratio (MDR). We define success rate as a probability of success for information to travel beyond a certain location and message delivery ratio 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 and independently in a given area. However, in real traffic the movement of, and positions of vehicles are not independent of each other. Therefore, 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.

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

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

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

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

PERFORMANCE MEASURES

The approach to measure *success rate* and *message delivery ratio* from an information source to an equipped vehicle at location x is based on 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.

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For 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 $(i = 0,\dots,M)$
- $I_i(x)$: Indicator function for message reception at location x in the i_{th} simulation

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

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

, (   )

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 information which is especially useful 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 our 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*).

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

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, vehicles are equally spaced on the road and 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*).

When a simulation is completed, *ns*-2 generates a trace (*.tr) text file which is then analyzed using a scripting language such as perl and awk. In our study, 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.

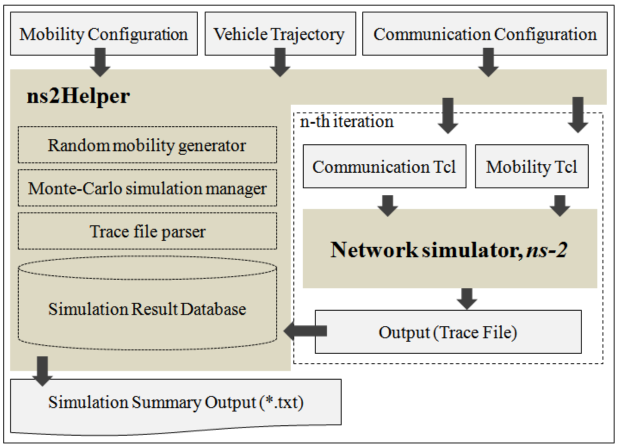
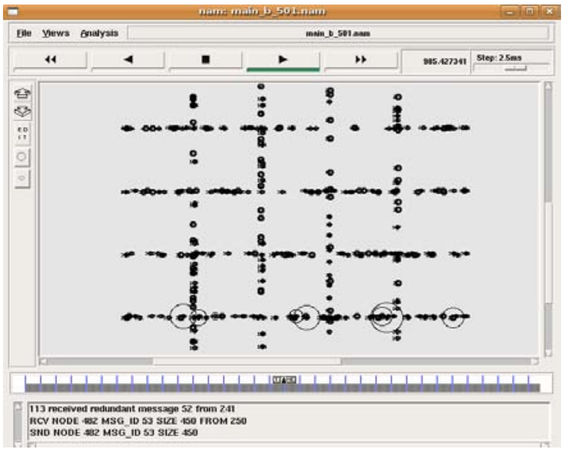


Figure 1. Simulation Framework



```
113 received redundant message 52 from 241
RCV NODE 482 MSG_ID 53 SIZE 450 FROM 250
SND NODE 482 MSG_ID 53 SIZE 450
```

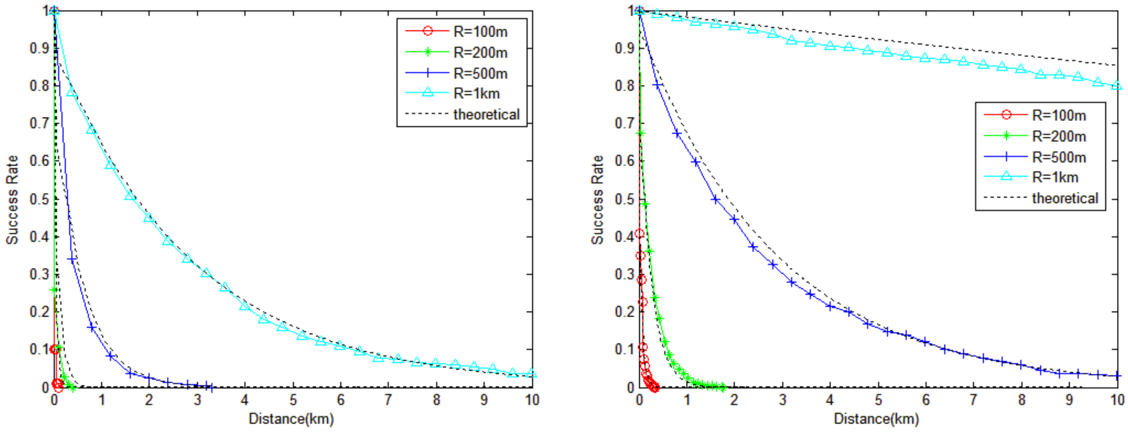
Figure 2. *ns*-2 simulation

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 an analytical model (*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.

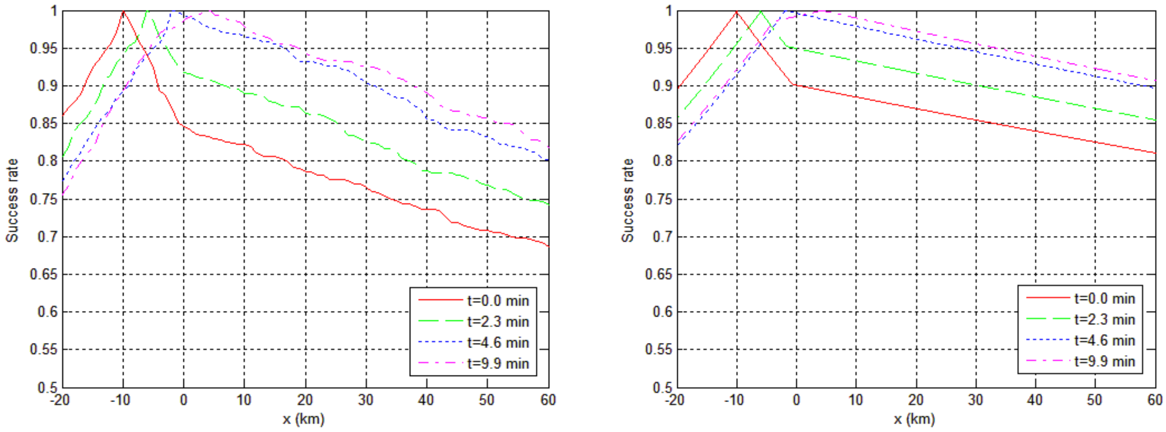
Transmission range (R)	Traffic density (ρ) and MPR 10 % (μ = 0.1)	
	ρ_1 = 20 veh/km	ρ_2 = 56 veh/km
R = 0.1 km	105.6 m	133 m
R = 0.2 km	232.22 m	422.30 m
R = 0.5 km	873.14 m	2799.66 m
R = 1.0 km	3572.72 m	> 20 km

Tabble 1. Average Information Propagation Distance

Table 1 illustrates the maximal value of average information propagation distances from the information source with the specified transmission ranges and traffic densities. Note that the average maximum information propagation distances are generally greater than the transmission range. 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

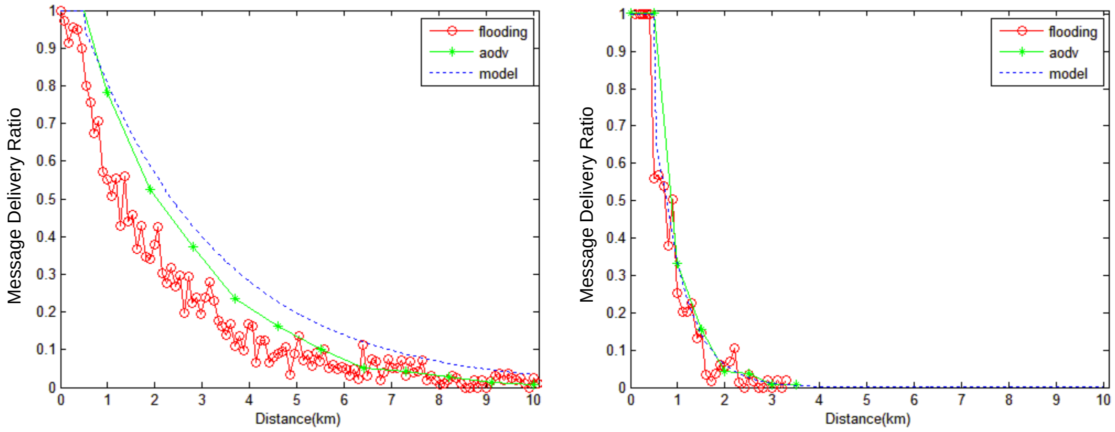
Figure 4 shows the success rates in both forward and backward directions at four instants of time: t_0 = 0, t_1 = 2.3, t_2 = 4.6, and t_3 = 9.9 minutes. In the simulation, the corresponding locations of information source are -10 km, -6 km, -2 km, and 4.3 km, and the locations of shockwaves are 0 km, -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 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 (*32*) over M = 500 simulation runs.

IMPACT ON 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.



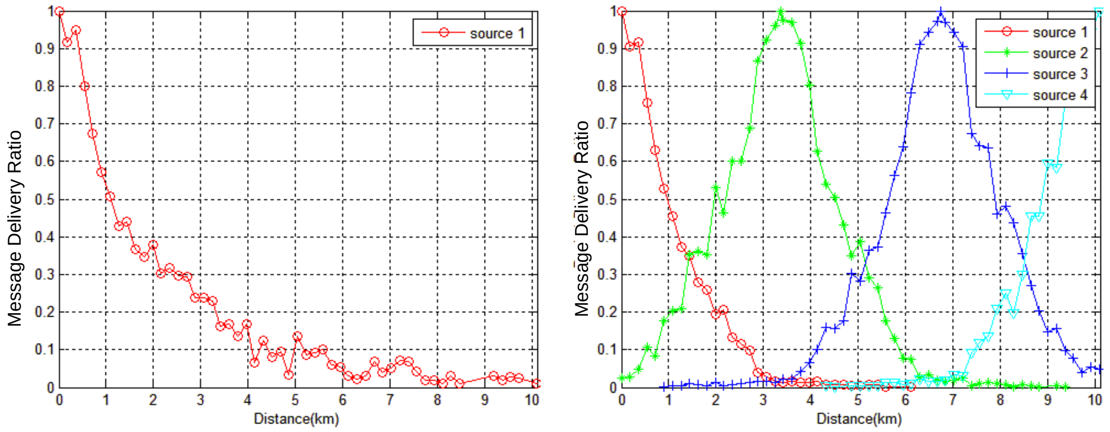
5(a) ρ_1 = 56 veh/km **5(b) ρ_2 = 20 veh/km**

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

Figure 5 presents message delivery ratio for two different traffic densities with R = 500 m. 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. The lower message delivery ratio in flooding for higher traffic density is 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 ON 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.

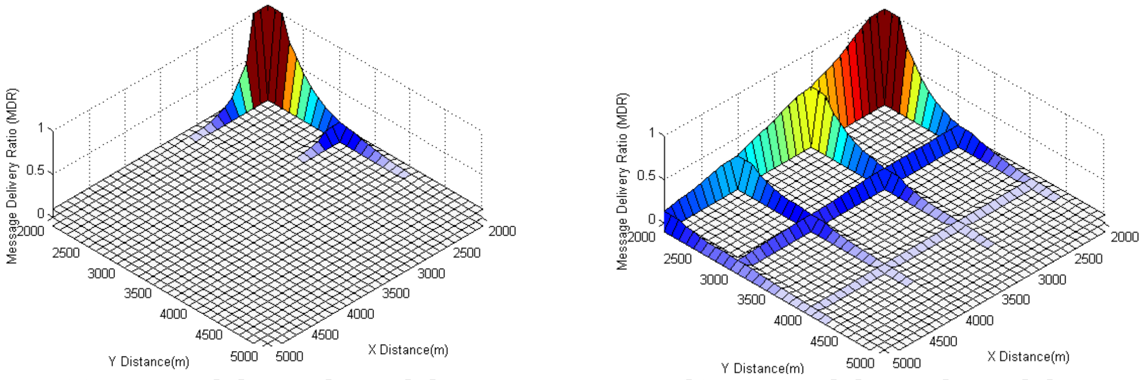


6(a) Single Information Source **6(b) Four Information Sources**

Figure 6. Message Delivery Ratio with Multiple Sources

IMPACT ON 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. We designate the four longitudinal traffic flows to 30 veh/km and vary the four latitudinal traffic flows 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 (covering 3 intersections) and 60 veh/km 5 km (covering 12 intersections). This is due, in part that as traffic flow meets at an intersection information can be propagated further. Hence, Figure 7(b) shows significant gains in message distance traveled by doubling the traffic density.



7(a) ρ = 15 veh/km and 30 veh/km **7(b) ρ = 60 veh/km and 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 inter-vehicle communications. 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.

To measure the performance of IVC, we consider *success rate* and *message delivery ratio*. First, we measure *success rate* for both uniform traffic and shockwave traffic. The result shows that both traffic density and transmission range 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 causes greater interferences that lead to more packet drops. Both traffic and network can significantly impact the performance in inter-vehicle communication.

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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 simulation challenges such as time-synchronization between the two simulators and ensuring compatibility and portability. 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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Broadcasting Safety Information in Vehicular Networks: Issues and Approaches

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Abstract

A primary goal of intelligent transportation systems is to improve road safety. The ability of vehicles to communicate is a promising way to alleviate traffic accidents by reducing the response time associated with human reaction to nearby drivers. Vehicle mobility patterns caused by varying traffic dynamics and travel behavior lead to considerable complexity in the efficiency and reliability of vehicular communication networks. This causes two major routing issues: the broadcast storm problem and the network disconnection problem. In this article we review broadcast communication in vehicular communication networks and mechanisms to alleviate the broadcast storm problem. Moreover, we introduce vehicular safety applications, discuss network design considerations, and characterize broadcast protocols in vehicular networks.

Every year, millions of traffic accidents occur worldwide, resulting in tens of thousands of casualties and billions of dollars in direct economic costs. For many years now, transportation planners have been pursuing an aggressive agenda to increase road safety through intelligent transportation system (ITS) initiatives. Furthermore, in 2001 the European Transport Policy set out a goal to reduce road fatalities by 50 percent by the year 2010. Similarly, in 2008 the U.S. Department of Transportation's (DOT's) Research and Innovative Technology Administration challenged the industry to reduce 90 percent of traffic crashes by 2030. 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 U.S. IntelliDrive and European eSafety programs. A novel communication system known as dedicated short-range communication (DSRC) has been proposed within the 5.8–5.9 GHz frequency spectrum allocated for its use. Standard activities for the overall system architecture and communication framework are coordinated by a variety of entities that include the IEEE (IEEE 802.11p, IEEE 1609 working group) in the United States, and the Car 2 Car Communications Consortium (C2C-CC), European Telecommunications Standards Institute (ETSI, TC ITS), and International Organization for Standardization (ISO, TC204/WG16) in Europe and other parts of the world.

To achieve the future road safety vision, time-sensitive, safety-critical applications in vehicular communication networks are necessary. Broadcasting will play an important role in disseminating safety messages to all nearby vehicles such as look-ahead emergency warnings and information about unsafe driving conditions. However, the lack of packet acknowledgment, packet retransmission, and a medium reservation scheme makes it difficult to achieve high broadcast reliability and efficiency in dense vehicular networks due to wireless contention and interferences.

The Routing Problem

The fundamental design consideration for routing protocols is the network environment and whether it is a static or dynamic network. Design in the underlying communication system is complicated by requirements that satisfy multiple constraints which include high reliability, efficiency, and scalability performance measures.

A vehicular ad hoc network (VANET) is a specific type of mobile ad hoc network (MANET) where dynamic routing protocols are necessary. A VANET operates in a self-organized manner without permanent infrastructure and, similar to a MANET, encounters two major routing issues, the broadcast storm problem and the network disconnection problem. The broadcast storm problem occurs when mobile nodes send messages by flooding, causing frequent link layer contention with other nearby broadcasting nodes that result in high packet loss due to collisions. Specifically, this phenomenon happens during multihop relay and message broadcast. Multihop relay occurs in MANETs in wireless mesh configurations and in VANETs when there are no roadside stations nearby. For MANETs, message broadcast occurs during route discovery or route maintenance, such as route request *hello* messages. For VANETs, this happens in periodic broadcast beacons of vehicle or traffic information. Achieving high communication reliability and efficiency is an essential requirement for safety-based ITS applications. Furthermore, the network disconnection problem for VANETs is more severe than for MANETs due to high mobility caused by fast moving vehicles and the sparse traffic densities during off-peak hours. This disconnection time (on the order of a few seconds to several minutes) makes MANET protocols such as Ad Hoc On Demand Distance Vector unsuitable for VANETs.

Hence, new network designs to improve broadcast reliability in dense networks and routing decisions in sparse networks are necessary. In this article we review existing methods and design considerations for vehicular communication networks. In partic-

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ular, our discussion includes application requirements, communication systems, traffic characteristics, and routing protocols. We conclude by summarizing the lessons learned, field experiments, and future challenges of broadcasting in vehicular communication networks. In the literature previous surveys and tutorials on routing protocols for VANETs have been explored by [1–7]. This article is an extension from these related works as it focuses on broadcast methods with an emphasis on the design requirement of high reliability and efficiency for vehicular safety applications by alleviating the broadcast storm problem.

Design Considerations

Safety Applications

Specific ITS applications govern the performance requirements in vehicular communication networks. During phase one DSRC experiments, several road safety scenarios based on cooperative intersection collision avoidance systems were tested. These scenarios included traffic signal violation warnings, stop sign alerts, and left turn signal assistance. According to the U.S. Vehicle Safety Communications Consortium, a comprehensive list of more than 75 application scenarios for intelligent vehicle safety applications enabled by DSRC have been identified [8]. Table 1 describes a list of safety applications, and their corresponding communication and traffic parameters. In particular, safety applications at intersection roads (infrastructure-to-vehicle) and message exchange among vehicles (vehicle-to-vehicle) have the most promising safety benefits in the near and mid-term future.

Message transmit mode can be triggered periodically or event-driven. In the periodic case, preventive safety messages are disseminated to keep drivers informed with details such as forward and opposing vehicle speed, acceleration, and deceleration values. On the other hand, event-driven messages are delivered occasionally as in the case of a sudden hard braking vehicle from other nearby vehicles or emergency vehicles such as ambulances. Moreover, many applications that send event-driven messages are relevant for farther vehicles, allowing upstream vehicles to undertake early countermeasures to prevent severe catastrophes such as chain-reaction accidents.

In Table 1 the latency for safety requirements are approximate values proposed previously by several sources that include previous research papers, automotive practitioner recommendations, and consortium reports. In addition, preliminary evaluation in field tests indicate the typical delay requirement for many safety applications is between 100 and 500 ms, a lower bound value compared with human reaction time. The delay factor for safety applications is important, and the IEEE 802.11p specification has set a minimum allowable latency of 100 ms for periodic message broadcast. In general, near real-time information is essential as even non-safety traffic-based applications require delay latencies in the range of several seconds to a few minutes for many ITS applications to be useful. The maximum communication range depends on usefulness of the safety information to nearby vehicles for both upstream and downstream traffic in the same direction for highways, as well as opposing directions on arterial roads and local streets. In situations where the maximum communication range does not reach the intended distance, multihop communication is a useful mechanism.

Communication

In communication networks packet delivery can be unicast, multicast, or broadcast. The behavior of multicast and broadcast systems are different, as the former sends a message to multiple destinations based on specific group attributes, while the latter sends a message to all recipients within its coverage area. In vehicular communication networks, for example, a group of taxi or courier vehicles in a metropolitan city may only relay messages among their fleets. However, an ambulance siren alert must notify all nearby vehicles to pull over rapidly and safely. In recent years other forms of network delivery have been proposed that include geocast and anycast. In particular, for vehicular networks geocast, which is based on geographic routing, has been studied extensively by taking a form of greedy forwarding in relaying information to the destination such as most forward within range (MFR) or nearest with forward progress.

Different from other wireless networks, packets in vehicular networks are mostly autonomous and have specific temporal and spatial relevance. Furthermore, the assumptions may include knowledge of digital road layouts, location coordinates (GPS), and in some cases the location of the destination node. Performance metrics that are important include message delivery ratio, packet reception rates, packet error rates, and end-to-end transmission delay. A comprehensive classification of different automotive applications in DSRC and detailed performance measures for VANETs is reviewed in [9].

Traffic

The mobility patterns of communication nodes in VANETs are significantly different from those in conventional wireless networks. Vehicles' space-time trajectories are restricted by paved roadways and drivers' choices of origins, destinations, departure times, and routes. The positions of vehicles are not independent on a road due to car following or lane changing rules. Densities of vehicles can vary dramatically along a communication path due to driving behaviors and restrictions caused by network geometry.

Previous studies have shown that the topological properties and mobility models can have dramatic impact on network protocol performance. Two popular mobility models for vehicular communication that generate movements at the microscopic level include SUMO and VanetMobiSim, incorporating aspects of the car following model developed by Stefan Krauss and the TSIS-CORSIM traffic simulator. An in-depth survey and taxonomy of mobility models for VANETs is described in [10].

Furthermore, vehicle movements can be complicated by other factors such as traffic signals and stop signs in arterial roads and ramp meters on highways. Traffic simulators such as TransModeler and Paramics that incorporate traffic flow theory and traffic control systems can provide greater realism in vehicle trajectories. Another approach to formulating the topological properties and mobility model involves using realistic vehicular traces to account for other variables. Some research work has adopted this method, using mobility trace data from SUVnet (taxi traces via GPS) and BTL/NG-SIM (vehicle traces via loop detectors).

Overview of Broadcasting Protocols in Vehicular Networks

In this section we present a classification of broadcast protocols based on methods to reduce the broadcast storm problem for vehicular communication networks. Table 2 illustrates the historical taxonomy of broadcast communication with a qualitative comparison of the communication methods, traffic characteristics, network simulation environment, and mobility model used in the protocol design and evaluation. In certain cases the literature on broadcast protocol did not specify the simulation environment, road topology, and mobility models used in their evaluation. For these situations, we omit their discussion and leave the table field entries blank.

	Safety application	Communication type	Traffic information	Transmit mode	Latency (ms)	Communication range (m)
Intersection collision avoidance	Traffic signal violation warning	Infrastructure-to-vehicle	Traffic signal status and timing; pedestrian crossing	Periodic	~100	≤ 250
	Left turn assistant	Vehicle-to-infrastructure Infrastructure-to-vehicle	Traffic signal status and timing; vehicle position, speed, heading; intersection road shape	Periodic	~100	≤ 300
	Stop sign movement assistance	Vehicle-to-infrastructure Infrastructure-to-vehicle	Vehicle position, heading, speed	Periodic	~100	≤ 300
	Intersection collision warning	Vehicle-to-vehicle	Vehicle position, heading, speed; turn signal status	Event-driven	~100	≤ 300
	Blind merge warning	Infrastructure-to-vehicle	Vehicle position, speed, heading	Periodic	~100	≤ 200
	Pedestrian cross information at designated intersections	Infrastructure-to-vehicle	Pedestrian detection and crossing	Periodic	~100	≤ 200
Information from other vehicles	Cooperative collision warning	Vehicle-to-vehicle	Vehicle position, speed, heading, acceleration	Periodic	~100	≤ 150
	Emergency electronic brake lights	Vehicle-to-vehicle	Vehicle position, heading, speed, deceleration	Event-driven	~100	≤ 300
	Highway merge assistant	Vehicle-to-vehicle	Vehicle position, heading, speed; vehicles in merge path	Periodic	~100	≤ 250
	Blind spot warning	Vehicle-to-vehicle	Vehicle position, heading, speed	Periodic	~100	≤ 150
	Pre-crash sensing	Vehicle-to-vehicle	Safety sensor coordination on seatbelts, airbags, pre-arming	Event-driven	~20	≤ 50
	Transit vehicle signal priority	Vehicle-to-vehicle	Vehicle position, heading, speed	Event-driven	~1000	≤ 1000
	Cooperative vehicle-highway automation systems (platoon)	Vehicle-to-vehicle Vehicle-to-infrastructure	Vehicle headway distance, position, speed; coordinated platoon maneuvers	Periodic	~20	≤ 100
	Cooperative adaptive cruise control	Vehicle-to-vehicle	Vehicle headway distance, vehicle cut-in	Periodic	~100	≤ 150
Public safety	Approaching emergency vehicle warning	Vehicle-to-vehicle	Emergency vehicle right-of-way yield	Event-driven	~1000	≤ 1000
	Post-crash warning	Vehicle-to-infrastructure Vehicle-to-vehicle	Disabled vehicle due to crash or mechanical breakdown	Event-driven	~500	≤ 300
Sign extension	In-vehicle signage	Infrastructure-to-vehicle	Signage typically conveyed by traffic signs (e.g., school zone, speed limit)	Periodic	~1000	≤ 200
	Curve speed warning	Infrastructure-to-vehicle	Curve location, curve speed limits, curvature, road surface condition	Periodic	~1000	≤ 200
	Work zone wWarning	Infrastructure-to-vehicle	Distance to work zone, road closure, reduced speed limit	Periodic	~1000	≤ 300

Table 1. *Vehicular safety applications: communication requirements and traffic information.*

Communication Characteristics

In the MANET literature several suppression schemes have been proposed to improve the overall reliability of the shared communication channel. These schemes include probabilistic-based, counter-based, distance-based, and location-based methods. These schemes have been adopted in broadcasting for vehicular communication networks along with new methods such as cluster-based and traffic-based methods. In location- and position-based methods, messages are broadcast based on the geographic area of the transmitting and receiving vehicle locations. In distance and hop-based methods, messages are broadcasted by considering the neighboring distances and hop count from the transmitting node. Cluster-based

	Location-/position-based	Distance/hop-based	Cluster-based	Proba-bilistic-based	Network simulator	Traffic-based	High-ways	Arterials/local streets	Data aggrega-tion	Mobility model
Broadcast protocols	**Communication characteristics**					**Traffic characteristics**				
UMB, 2004	√	√			WS		√	√		Negative exponential (headways) and Gaussian (speed)
TrafficView, 2004					ns-2	√	√	√	√	Random waypoint model
MDDV, 2004	√				QualNet		√	√		CORSIM and Atlanta road traces
ODAM, 2004	√	√			ns-2					
OAPB/DB, 2005	√		√	√	ns-2			√		
AMB, 2006	√				WS			√		Negative exponential (headways) and Gaussian (speed)
SB, 2006	√	√								Negative exponential (headways)
MHVB, 2006	√				ns-2		√			Microscopic traffic simulator
D-FPAV, 2006		√			ns-2		√			DaimlerChrysler road traces
TRRS, 2007		√					√			
REACT, 2007	√				ns-2	√	√			Nagel and Schreckenberg cellular automata
DV-CAST, 2007				√						
FB, 2007		√								
DBAMAC, 2007			√		ns-2		√			IMPORTANT mobility tool
PAB, 2008	√			√	ns-2	√	√			Road Design Manual
REAR, 2008				√	ns-2		√			Manhattan model
CTR, 2009	√	√			ns-2		√			

Table 2. *Classification of broadcast protocols in vehicular networks.*

methods broadcast messages to vehicle groups, for example, to a platoon of vehicles with common paths. In probabilistic-based methods, messages are broadcast with a given probability p, and in many cases this probability is based on the protocol's backoff timer. For traffic-based methods, information on traffic dynamics such as vehicle speed are incorporated into the message broadcast decision. The predominant network simulation used is the state-of-the-art open source *ns*-2 simulator. A variety of mobility models are used for simulating vehicle movements in highway and arterial roads.

Urban Multihop Broadcast (UMB) and Ad Hoc and Multihop Broadcast (AMB) — In these techniques, preference on a broadcast relay and suppression scheme is utilized based on road location or vehicle position. To reduce the multihop messaging, UMB and AMB elect vehicles farthest away (MFR) from the information source as relay nodes. This location metric is computed based on the black-burst method, which lets receivers send black-burst signals proportional to their location from the source. Furthermore, the AMB protocol is an enhancement to UMB that does not require repeaters (infrastructureless) when vehicles may not be in the intersection to retransmit a message by nominating the node closest to the intersection position as the relay node for broadcasting instead.

Smart Broadcast (SB), Position-Based Adaptive Broadcast (PAB), and Distributed Vehicular Broadcast (DV-CAST) —SB and PAB use a dynamic backoff timer for medium access control (MAC) contention window adjustment to improve the efficiency of packet transmissions. SB's backoff timer scheme is based on the sender and receiver node distance, while PAB determines the backoff timer based on vehicle position and vehicle speed. DV-CAST uses local one-hop neighbor topology to make routing decisions. The protocol adjusts the backoff timer based on the local traffic density, and computes forward and opposing direction connectivity with periodic heartbeat messages. Moreover, DV-CAST is adaptive to the totally disconnected network and can temporarily wait-and-hold a packet until the vehicle hears heartbeat messages from other vehicles.

Multihop Vehicular Broadcast (MHVB) — MHVB adjusts the packet transmission interval with a position-based method. The two proposed schemes for packet retransmissions in MHVB include the location between sender and receiver, and the traffic congestion level, which is determined by a multitude of threshold values that include number of nearby vehicles, number of vehicles in forward and opposing directions, and vehicle speed. A subsequent improvement for MHVB was later published that includes more efficient angular coverage from sender to receiver and introduces a dynamic scheduling algorithm that prioritizes received packets.

Mobility-Centric Data Dissemination Algorithm for Vehicular Networks (MDDV) — MDDV is a geo-cast protocol that defines the destination region and trajectory-based routing based on travel directions to deliver packets to the region. The MDDV protocol runs a localized broadcast routing algorithm to continuously forward messages to the head node in the cluster pack and moves closer to the intended destination. Results from MDDV indicate that the routing protocol performance depends on the market penetration rate of vehicle-to-vehicle communication and road traffic density, which is affected by the time of day with its realistic movement traces.

Fast Broadcast (FB) and Cut-Through Rebroadcasting (CTR) — FB is a distance-based protocol that minimizes forwarding hops when transmitting messages and contains two components, the estimation and broadcast phases. In the estimation phase the protocol adjusts the transmission range using heartbeat messages to detect backward nodes. In the broadcast phase it gives higher priority to vehicles that are farther away from the source node to forward the broadcast message. CTR also gives higher priority to rebroadcast alarm messages to farther vehicles within transmission range but operating in a multichannel environment.

Distributed Fair Transmit Power Assignment for Vehicular Ad Hoc Network (D-FPAV) — D-FPAV describes a scheme that provides fairness in broadcasting heartbeat messages by dynamically adjusting every node's transmission power based on distance to other neighboring nodes. The method enables all nodes to share the channel capacity fairly. Although power control and adjustment is well explored in wireless networks, D-FPAV is unique as it investigates the problem in the context of broadcasting in vehicular networks by using realistic movement traces obtained from DaimlerChrysler on a German highway.

Dynamic Backbone-Assisted MAC (DBA-MAC) — DBA-MAC is a cluster-based broadcast for message propagation based on cross-layer intersection in the MAC. For a group of interconnected vehicles, higher-priority nodes within the cluster are considered backbone members and are able to broadcast messages. The process of choosing backbone nodes within the cluster occurs periodically by selecting nodes that are farther apart to minimize hop count.

Receipt Estimation Alarm Routing (REAR) — In the REAR protocol, nodes that relay broadcast messages are selected based on estimated message delivery ratio. This is computed based on the received signal strength and packet reception rates for packets that nodes receive, and this information is exchanged with neighboring nodes using heartbeat broadcast messages. Hence, nodes with higher message delivery ratios are likely candidates to flood messages in the network while the other nodes are kept silent to alleviate wireless contention conflict.

TrafficView — The TrafficView protocol is a part of the broader e-Road project with the goal of building a scalable and reliable infrastructure for intervehicle communication systems. In TrafficView, the message data contain information on a list of vehicle IDs and the vehicle's own position and speed, as well as broadcast duration time. TrafficView conserves bandwidth and deals with flow control of broadcast messages by aggregating multiple data packets based on relative vehicle distance and message timestamp. For example, two vehicles on the same highway lane traveling at similar speeds are likely to have similar vehicle positions and vehicle trajectories. Hence, when updated information on vehicle positions is available, vehicle speeds may not be necessary, which reduces packet size and results in lower packet transmission delay (less air time).

Time Reservation-Based Relay Node Selection (TRRS) and Routing Protocol for Emergency Applications in Car-to-Car Networks Using Trajectories (REACT) — TRRS proposes a method where nodes in the communication range choose their waiting time based on a specified time window. The time window is determined by a distance that is inversely proportional to the previous relay node and reservation ratio of the time window. A node with higher reservation ratio will have received duplicate broadcast messages and incurred longer time window waiting duration in the next transmission round. REACT gives more influence on the forwarding trajectory and angle, and integrates the position-based information with the time-division multiple access 802.11 MAC.

Optimized Dissemination of Alarm Message (ODAM) and Optimized Adaptive Probabilistic Broadcast and Deterministic Broadcast (OAPB/DB) — ODAM has a "defertime" to broadcast messages, computed based on the inverse proportional distance between receiver and source node. For ODAM, broadcast messages can only occur within the risk zone region, determined with a dynamic multicast group based on vehicles' proximity to the incident site. OAPB/DB uses an adaptive approach to rebroadcast emergency warning messages near the incident zone. Nodes rebroadcast messages probabilistically within the region based on the delivery ratio, which is computed based on local traffic density information.

Lessons Learned, Field Experiments, and Future Challenges

Lessons Learned

An overview of broadcast protocols in vehicular communication networks has been introduced. Specifically, these protocols address the broadcast storm problem by reducing packet redundancy, wireless contention, and collisions in the network. Although numerous design methods have been proposed, each protocol has its limitations and assumptions that may cause certain issues. For instance, the concept of node selection for multihop relay based on node distance (MFR), although reducing the total number of traveling hops, incurs a reliability trade-off with lower packet reception rates due to the loss in radio power from longer propagation distances. Also, several broadcast protocols to modify the MAC with different priority schemes have been proposed. However, such schemes may result in "unfairness" in the overall system where certain nodes have more packet transmission rounds than others. Yet another shortcoming for some methods is the assumption that GPS is readily available to provide location position to neighboring vehicles. Hence, the feasibility of these vehicular communication network applications will depend largely on the technology adoption and market penetration rates of vehicles equipped with capabilities, GPS devices, or both.

Field Experiments

In the past few years field trials have been conducted to fine-tune the DSRC specification. Initial results indicate packet error rates (PERs) can be highly affected by urban canyons, caused by radio signal degradation due to multipath fading [11]. The vehicle height profile can also significantly impact the transmission range for DSRC. Initial road test experiments indicate 20 percent PER with about 150 messages/s, and the results are better for shorter (300 bytes) rather than longer (1200 bytes) messages since longer packet length consumes more air time. The phase one stage provides a strong proof of concept for DSRC. However, VANETs still have many issues to address, including external factors such as road terrain conditions, vehicle types, and environmental factors.

Future Challenges

There remain many open issues and future challenges to solve. The field of vehicular networks has not only fostered academic research interest, but has motivated experts to publish books to share knowledge, most recently in 2009 [12–15] and 2010 [16, 17]. In the lower layers of the communication stack, novel channel access methods, priority access with IEEE 802.11e, dynamic contention window and power adjustment, and multiradio interfaces are just some of the techniques that can improve vehicular communication by optimizing the wireless channel load. This can be thought of as a scalability problem and characterized by the "communication density" metric for vehicular communications [18]. An empirical analysis using 802.11 wireless interfaces in the ORBIT emulation testbed provides some insights on the complexity of broadcasting in dense vehicular networks [19]. However, the communication parameters and how these contribute to the overall system reliability and efficiency are not yet well understood and need further analysis. Moreover, the design of vehicular communication networks needs to be integrated with the safety and traffic-based application requirements. For example, the communication system can dynamically consider the latency requirement in Table 1 and fine-tune its MAC contention window size to the desirable performance measures (e.g., highest delivery ratio, minimum delay).

Initially, the requirements will be for vehicular safety applications. Multihop broadcasting is useful to provide an early countermeasure to prevent catastrophes such as chain-reaction accidents for nearby and following vehicles in the upstream. Subsequent enhancements will include real-time traffic information and environmental applications that reduce emissions in vehicle platoons by stabilizing traffic on the road through adaptive cruise control. In other cases ITS traffic applications may tolerate small delay and allow messages to be queued at intermediate relay points prior to sending information to the intended destination when the network is sparse. In such cases a delay-tolerant geocast protocol that sends messages on demand based on time factors when near other vehicles or a traffic collection roadside station is more appropriate. Finally, security in VANETs remains a rich research area with many problems that need to be addressed including vehicle anonymity, message integrity, and authentication, traceability, and revocation of malicious attackers.

Conclusion

In this article we classify and survey broadcast protocols for vehicular communication networks. Vehicular networks have many safety-based applications where reliability is of utmost importance. Reducing message flooding serves as a fundamental method to alleviate the broadcast storm problem and increase the reliability and efficiency of disseminating safety messages to other vehicles. Future research for network engineers and researchers should incorporate traffic characteristics and application requirements into the communication system design. Traffic flow dynamics, along with improvements in the communication stack, will be important in designing reliable, efficient, and scalable broadcast methods for vehicular communication networks.

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Multi-Hop Broadcasting in Vehicular Ad Hoc Networks with Shockwave Traffic

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***Abstract*- A primary goal of intelligent transportation systems (ITS) is to improve road safety. The ability for vehicles to communicate is a promising way to alleviate traffic accidents by reducing the response time associated with human reaction to nearby drivers. In addition the limitations of standard driving can be overcome by providing drivers with instantaneous information about complications up ahead. Shockwaves, induced by vehicle speed differentials, are a typical mobility pattern that occurs with the formation and propagation of vehicle queues and increase the probability of traffic incidents. These induce sudden braking and increase the occurrence of traffic incidents. In this paper, we investigate safety applications in highways with shockwave mobility and different lane configurations in vehicular ad hoc networks (VANET). We evaluate the performance of multi-hop broadcast communication using the *ns*-2 simulator with vehicles following a shockwave mobility pattern in fully-connected traffic streams. We propose mechanism to improve broadcast reliability using dynamic transmission range that leverages our understanding of fundamental traffic flow relationships.**

I. INTRODUCTION

Every year, millions of traffic accidents occur worldwide, resulting in tens of thousands of casualties and billions of dollars in direct economic costs. For many years now, transportation planners have been pursuing an aggressive agenda to increase road safety through the ITS initiative such as the U.S. IntelliDrive and Europe eSafety projects. With the widespread adoption of wireless communication devices, vehicular communication is becoming an essential and emerging technology to allow vehicles to share or propagate useful information for drivers such as traffic congestion alerts, safety warnings, and traffic management suggestions. In the United States, in particular, the Federal Communication Commission (FCC) has allocated a spectrum of 75 MHz in 5.9 GHz for Dedicated Short Range Communications (DSRC), a technology for the ITS to improve road safety and complementary traffic information with standardization efforts described in IEEE 802.11p.

.Due to the time-sensitive, safety-critical applications in VANET, broadcasting will play an important role in vehicular communication to disseminate messages such as look-ahead emergency warning and information about unsafe driving conditions. However, the lack of packet acknowledgement and packet re-transmission makes it difficult to achieve high broadcast reliability due to wireless contention and interferences in the medium. Unlike unicast, the optional RTS/CTS handshake to prevent the hidden terminal problem in 802.11 cannot be used for broadcast since the RTS/CTS exchange would cause even more packet flooding and exacerbate the broadcast storm problem. The motivation for our work derives from previous studies that suggest the importance of examining the impacts of mobility patterns and transportation network configurations on vehicular communications. The work by [1] suggests these factors can significantly impact multi-hop connectivity with vehicular communications in both uniform and non-uniform traffic streams. As such, we explore the impacts of network environment on highways with different lane configurations and mobility patterns on the performance of multi-hop broadcasting.

In VANET, maintaining high connectivity and high broadcast reliability is difficult, especially in dense networks and with non-homogeneous vehicle mobility. In this paper, we propose a mechanism to dynamically control the communication range for vehicles by adjusting the transmission power to mitigate the effects of broadcast storm. Specifically, our safety-application scenario relates to shockwave on highways, a common phenomenon that occurs every day along with the formation and propagation of traffic queues. A shockwave separates two traffic streams with different traffic densities and speed, derived according to the fundamental traffic flow relationships. When the first vehicle in the following traffic stream meets the last vehicle of the leading traffic stream, it senses the danger and immediately sends a broadcast message to inform all nearby vehicles (within a few kilometers away) of an upcoming shockwave and caution the vehicles to reduce speeds. The information propagation is relayed from one vehicle to the next, inspired by the need for multi-hop broadcast [2]. Previous work in wireless multi-hop networks [3] shows the benefits of dynamic transmission power control (which results in a dynamic transmission range) as a way to increase network capacity at the same time as reducing power consumption.

The contribution of this paper is a simulation-based approach for a better understanding on the performance of multi-hop broadcasting under shockwave mobility on highway with different lane configurations. Efficiency in packet reception is achieved by reducing packet collisions caused by overhearing broadcast packets through transmission range adjustment based on vehicle speed variation. Further, we compare the performance of static and dynamic minimum transmission range for different lane configurations on the highway with free flow and congested traffic densities.

II. RELATED WORKS

The work by [4] uses a dynamic transmission-range assignment (DTRA) algorithm that employs transmission power control based on the relationship between connectivity and traffic density characteristics. Their approach uses an analytical traffic flow model to derive and estimate local density coupled with the RoadSim vehicle traffic simulator to measure the performance of the communication system on several road configurations. Further, the paper provides simulation results identifying the minimum transmission range for different traffic densities in non-homogeneous traffic that does not require any message exchange with neighboring vehicles. The focus of their work and the DTRA algorithm is to maintain a high level of connectivity in vehicular networks by estimating the local vehicle density and local traffic conditions (free flow versus congested traffic). In the communication model, they assume that two vehicles can communicate if their Euclidean distance is less than or equal to the shorter transmission range between the two vehicles. However, communication issues associated with radio interface such as contention in the shared transmission window, hidden terminals, and other errors were not considered in their study.

The work by [5] uses simulation traces to derive an empirical model that provides the broadcast reception rate probability. Parameter optimizations and their empirical model formulation include inspiration from *Jiang et al.* [6] that define channel load in vehicular communication by the product of traffic density, packet generation rate, and transmission range. The simulation scenario is a circular road but their results consider single-hop broadcast only with vehicles all having the same transmission range.

The work by [7] evaluates the performance metrics of delivery ratio and delay for broadcasting safety beacon messages with varying packet transmission interval and data packet sizes. The simulation methodology is similar to our environment, but their study is based on a fixed transmission range and does not consider multi-hop broadcasting.

The work by [8] proposes the distributed fair power adjustment for vehicular networks (D-FPAV) algorithm that dynamically adjusts each vehicle's transmission power (and hence transmission range) to prevent packet collisions. The optimization focuses on fairness of each communicating vehicle to receive and send safety information rather than network capacity and connectivity. Fairness in their adaptive transmit power scheme is validated through simulation results on highway scenarios with different radio propagation models.

The work by [9] proposes a multi-hop broadcast protocol called *Fast Broadcast* that reduces the time to propagate a message and reduces the total number of hops to cover a portion of the road. The scheme estimates forward and backward transmission ranges, computed using two rounds of transmission ranges (current-turn and last-turn). However, their scheme requires message exchange between vehicles in the specific area-of-interest to determine vehicle spacing and make transmission range adjustments accordingly.

The work by [10] uses simulation traces to present a broadcast protocol for intermittent connectivity in highway and urban traffic scenarios that improves reliability and efficiency by reducing redundant retransmissions. It uses periodic beacon messages to acquire neighboring vehicle locations and piggyback acknowledgments for reception.

In the MANET and VANET literature, previous proposed methods that avoid broadcast storm problem include hop-based, location-based, cluster-based, probabilistic-based, and traffic-based suppression schemes such as [11] and [12]. Our method to improve broadcast reliability integrates the vehicular communication system with traffic flow by dynamically adjusting transmission range based on traffic density and vehicle speed characteristics. Further, our study on multi-hop broadcast extends the potential application use cases. Single-hop broadcast are useful for high locality and very time sensitive applications such as crash imminent collision. However, it does not provide safety applications that stretch several miles for look-ahead warning to alert the downstream traffic for advance speed reduction. Finally, multi-hop broadcast communication may also have environmental applications that reduce emission in vehicle platoons by stabilizing traffic on the road through cooperative cruise control systems.

III. DESIGN

A. Traffic Scenarios

Our traffic scenario includes two traffic streams with each traffic stream stretching five kilometers and one kilometer apart with uninterrupted traffic flow. Market penetration rate (MPR) of equipped vehicle with communication device is 100% and vehicles are uniformly distributed according to their traffic density. Since shockwaves are caused by variation in speed differentials, the two traffic streams have different traffic density with the leading traffic stream's density greater than the following traffic stream. It is generally accepted that, for uninterrupted traffic flow, there is a density-speed relationship [13]. In our simulation, we assume the so-called triangular fundamental diagram [14] [15] with density ρ and speed V.

$$V(\rho) = \begin{cases} V_f & , \ 0 \le \rho \le \rho_c \\ V_f \left(\frac{\rho_c}{\rho_j - \rho_c}\right)\left(\frac{\rho_j - \rho}{\rho}\right) & , \ \rho_c \le \rho \le \rho_j \end{cases} \qquad (1)$$

We assume the conditions in which the free flow speed V_f = 104 km/h (64.6 mph), a reasonable value for highway speed limit. The jam density is ρ_j = 150 veh/km [16], and critical density $\rho_c = 0.2\,\rho_j$. Further, we assume density ρ_1 = 90 veh/km and ρ_2 = 30 veh/km for the two traffic streams with vehicle spacing 11.1 meters and 33.3 meters. Based on these assumptions for triangular fundamental diagram and the formulation in *(1)*, a lane consists of 600 vehicles with leading traffic stream vehicles traveling at 17.4 km/h (10.8 mph), following traffic stream vehicles at free flow speed. The backward shockwave speed is -26 km/h (16 mph). Specifically, our traffic scenario is relevant to a typical shockwave encounter on a highway where vehicles in the downstream are congested while the upstream vehicles are un-congested. The distance between vehicles on neighboring lanes is set to 3.65 meters according to the highway capacity manual. The shockwave pattern in the simulation is based on the speed-density relationship and parameters described above, and is created using MatLab and ported onto *ns*-2 mobility file. Figure 1 shows the trajectory of shockwave traffic in our scenario with each line representing vehicle's movement for a specific location and time instant. Moreover, the figure illustrates backward shockwave point propagation as vehicle reduces their speed with the congestion traffic ahead from 64.6 mph to 10.8 mph.

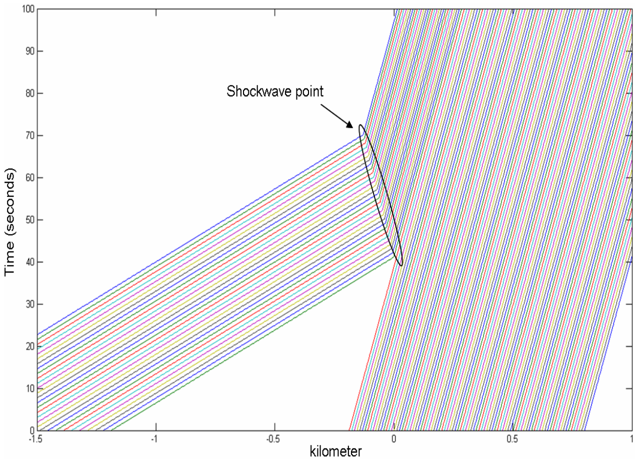

Figure 1. Trajectory of Shockwave Traffic

B. *Simulation Environment*

We use *ns*-2.33 network simulator to evaluate communication performance with the mobility model according to section 3-A. In the simulation, all nodes are configured to flood all un-heard messages to follow the multi-hop broadcasting behavior. To evaluate the impact of varying communication range and transmission power adjustment, we use the deterministic two-ray ground propagation for radio model. For higher fidelity with realistic vehicle-to-vehicle communications, we set configuration values according to the IEEE 802.11p draft standard. For security protection, we assign packet size to 382 bytes with 200 bytes of data payload, 128 bytes for a certificate, and 54 bytes for a signature similar to [5]. The main parameters used in the *ns*-2 simulation are presented in Table 1. The simulation ran on a 2.3 GHz quad-core with 8 GB RAM and the multi-core processors provide speed up in the Monte Carlo simulation.

Information source is the first vehicle of the following traffic stream that after 41 seconds detects the upcoming shockwave ahead and broadcast a shockwave alert message once in both upstream and downstream directions. For multiple-lane situations, we assume that the first vehicle (information source) originates from lane one. Sending the shockwave message alert to downstream vehicles on the same direction can be beneficial as those vehicles can later relay messages in the opposing direction of the highway for non-instantaneous forwarding.

TABLE I COMMUNICATION CONFIGURATION

Parameters	**Values**
Antenna height	1.5 m
Antenna gain	1 dB
RxTh	-95 dBm
CSTh	-99 dBm
CPTh	4 dB
Data rate	3 Mbps
Frequency	5.9 GHz
Packet size	382 bytes
Minimum contention window	15 slots
Number of messages send	1
Tx range (meters) Corresponding power (dBm)	37, 18.5 -15.8, -21.8

C. *Transmission Range Adjustment*

In our simulation, we use minimum transmission range (*MinTR*) which is computed based on the spacing distance between a leading and following vehicle. Since the MPR is 100%, the communication equipped vehicles are fully connected. We compare the results with fixed *MinTR*, derived using the value from following traffic density ρ_2 and dynamic minimum transmission range values for each traffic density ρ_1 and ρ_2. Note however the actual *MinTR* shown in Table 1 and used in our simulation is a few meters more to compensate for multiple lanes and flexibility that messages send by vehicle on lane one can be heard by vehicles one vehicle distance away for all lanes.

IV. SIMULATION RESULTS

A. *Discussion*

For statistical reliability and to avoid correlation in the results, a Monte Carlo approach of 500 runs (with varying seed in *ns*-2) for each scenario with different highway lanes is computed. Additional scripts were used to compute parse the raw output and compute performance measures of the collected data. In particular, we evaluate two performance metrics for multi-hop broadcasting, message delivery ratio (MDR) and packet reception rate (PRR). MDR is measured at the application level and defined by the probability of the message send by the information source to travel a certain distance along the traffic stream. PRR is measured in the MAC level and defined as the probability of packet reception for a given distance, measured in 100 meter segments. In the figures, performance measure starts at the information source where the first shockwave transition occurs (kilometer distance zero).

Figure 2 and Figure 3 shows the MDR and PRR for fixed transmission range for all vehicles, *MinTR=37*. Figure 4 and Figure 5 shows the MDR and PRR for dynamic transmission ranges where vehicles in traffic density ρ_1 are assigned *MinTR=18.5* and vehicles in ρ_2 with *MinTR=37*. Difference in the two traffic streams are attributed to the congested and free-flow traffic patterns. In the MDR measure, as the number of lanes increases for free flow traffic, the MDR also improves as shown in Figure 2 and Figure 4. Further, the result for two lanes is particularly low since it endures communication interferences from vehicles in the adjacent lane and its traffic density is least among all the multi-lane scenarios. In the case of congested traffic with fixed transmission range, the MDR achieves 100% with three or more lanes as it can fully reach the 5 km distances. However, in congested traffic with dynamic transmission range, only the one-lane scenario has guaranteed reliability as indicated in Figure 4. This is because for one lane case with *MinTR*, there is no contention in wireless medium and no interferences from other vehicles farther away in the forward and backward directions as well as adjacent lanes.

Contrary to MDR, the PRR shows opposite effect where more lanes result in lower packet reception rate. Further, Figure 3 illustrates that in all cases of fixed transmission range, there is a downward spike in PRR from the information source to its nearby downstream traffic. This is triggered by the transition from free flow and the increase in overall vehicle density in the congested traffic stream.

B. *Impact of Lane Configuration*

In our highway traffic scenario, the number of lanes affects the communication densities. This can be observed in both MDR and PRR results. As we describe earlier, the one lane scenario with *MinTR* is a special case that has the best results for all figures and lane configurations except in the forward direction in Figure 2. For the multi-level scenarios, the more lanes the higher the application level delivery probability. However, it comes at a tradeoff where greater traffic densities cause more collisions in the MAC level and results with lower packet reception. For the two lane scenario, the multi-hop broadcast message propagates only about half the entire 5 km in the direction of the free-flow traffic and its packet reception rates has higher volatility due to less overall received packets in comparison with three, four, or five lanes. Finally, the dynamic *MinTR* adjustment for two lanes in the direction of the congested traffic causes it to reach only about 1 km in distance.

C. *Impact of Transmission Range*

Although the transmission range adjustment for dynamic *MinTR* results in lower MDR, it can improve PRR. The analytical model proposed by [17] describes the relationship between application and communication level delivery ratios and its formulation shown in *(2)*.

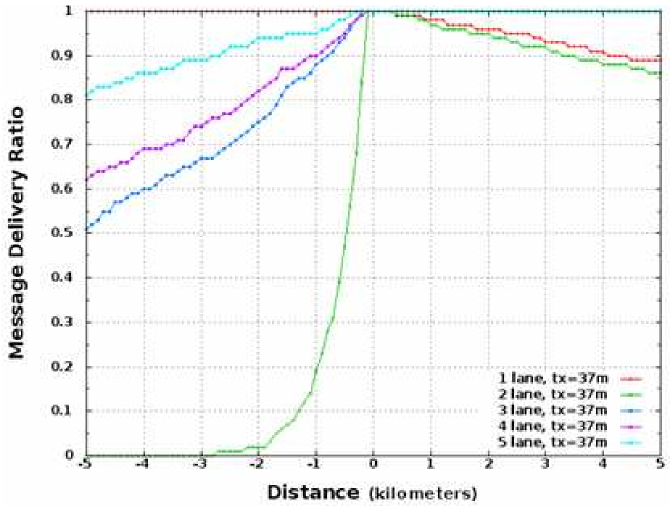

Figure 2. Message Delivery Ratio for Fixed Transmission Range

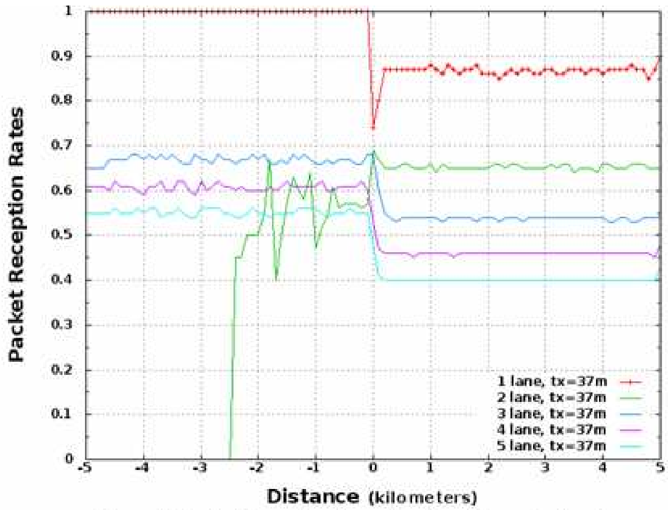

Figure 3. Packet Reception Rates for Fixed Transmission Range

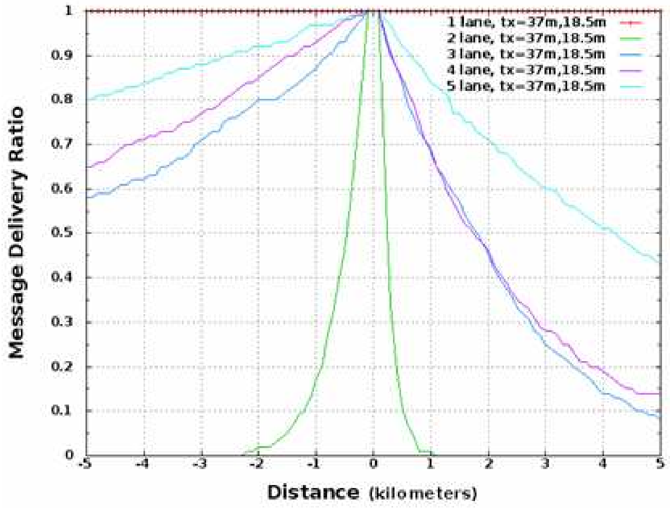

Figure 4. Message Delivery Ratio for Dynamic Transmission Range

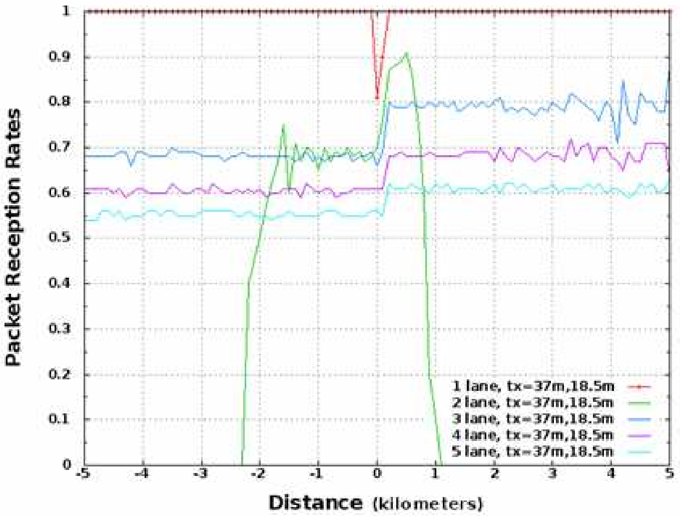

Figure 5. Packet Reception Rates for Dynamic Transmission Range

$$P_{\text{app}}(N) = P \text{ (at least 1 successful tx in } N \text{ tries)}$$
$$= 1\text{-}P \text{ (all fail in } N \text{ tries)} = 1\text{-}(1\text{-}P_{\text{com}})^N \quad (2)$$

The DSRC standard requires that the packet generation rate for safety messages are triggered every 100 milliseconds. Hence, the MDR delivery ratio can quickly be compensated in the case when multiple *N* messages are sent. Hence, the tradeoff of lower MDR to compensate for higher PRR with dynamic transmission range is desirable. Real field experiments by the USDOT RITA VII project on the communication performance also suggest the desire for low packet error rate as a design consideration for DSRC [18]. It is valid that it may be difficult to compute the absolute *MinTR* for different free-flow traffic densities since the vehicle speed would be the same. In fact, the DTRA algorithm suggests using maximum transmission range (*MaxTR*) since the less traffic density with free flow will have less impact on wireless medium contention and interferences. Our result on free-flow traffic is the critical density ($\rho_c = 0.2\ \rho_j$). Intuitively, for free-flow traffic, if the transmission range was rather set to *MaxTR*, the results should indicate the farthest distance travel with highest MDR and lowest PRR possible.

V. CONCLUSION AND FUTURE WORK

In this paper, we study the performance of multi-hop broadcasting on the highway traveling in one direction. We suggest a mechanism to improve multi-hop broadcast reliability and efficiency with dynamic transmission ranges based on our understanding of fundamental traffic flow relationships. In particular, we show the benefits of employing dynamic transmission ranges on the highway with shockwave mobility that inter-mixes free flow and congested flow traffic. Using *ns*-2 simulator, we evaluate the performance measure of message delivery ratio and packet reception rates. In addition, we show that lane configurations can have a major impact on the performance measures.

Future work can incorporate complex traffic and network characteristics for greater realism in shockwave mobility with non-homogeneous stop-and-go traffic pattern to describe heavy congestion. Moreover, message generation rate for sending messages multiple times or from multiple information sources are possible and can further clog the communication medium. Studies on dynamic contention window for broadcasting have been proposed by [19] and the metric of contention window adjustment and its formulation can incorporate traffic flow dynamics. Analytical methods to model the wireless contention and communication reliability and efficiency for safety-based DSRC systems have been studied recently by [20] [21]. Further, theoretical analysis on the results and relationship for delivery ratio in the application and communication level would be helpful for understanding the factors that impact the performance metrics in VANET. These methodologies can be beneficial in the routing protocol design for VANET.

VI. ACKNOWLEDGMENT

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Dynamic Transmission Range in Inter-Vehicle Communication with Stop-and-Go Traffic

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Abstract— **Inter-vehicle communication is a promising way to share and disseminate real-time and nearby safety information on the road. However, several pressing open questions require solutions in order to achieve high reliability and efficiency with these systems. Further, previous studies have shown that the mobility model can significantly influence the communication performance in vehicular networks. In this paper, we analyze communication in stop-and-go waves and propose a method to optimize an important network parameter, the transmission range, based on traffic stability measures. Our findings suggest a transmission range adjustment scheme that achieves high reliability by considering network coverage and packet reception rates.**

I. INTRODUCTION

In recent years, computing systems and communication capabilities have become more affordable, powerful, and accessible. For example, the proliferation of smart phone computing devices has enabled more people to stay connected to the Internet over longer time spans. Similarly, this trend is now expanding to vehicles. The global positioning system (GPS) that integrates computing and satellite communication has resulted in millions of vehicle drivers with real-time road navigation information in the United States. Advanced telematic systems will only continue to grow and facilitate drivers with better and more accurate real-time traffic and safety information.

Dedicated Short Range Communication (DSRC) is a technology based on 802.11p that operates using 75 MHz of spectrum band in the 5.9 GHz range, and is specifically designed for automotive use in road safety and complementary traffic information. Due to the time-sensitive, safety-critical applications in VANET, broadcasting will play an important role in vehicular communication to disseminate messages about unsafe driving conditions to immediate nearby vehicles (one-hop) and other vehicles in the vicinity (multi-hop). However, there are several challenges to broadcast packets reliably. First, broadcast lacks acknowledgement (ACK) packets from the receiver. As a result, there is no retransmission of dropped packets. Due to this lack of MAC-layer recovery, the contention window size for broadcast is often held constant (fixed). This differs from unicast which adjusts the contention window size based on a binary exponential back-off scheme, depending on the packet failure probability. In addition, reservation schemes used in unicast such as RTS/CTS exchange cannot be efficiently used for broadcast since the nature of disseminating packets would exacerbate the broadcast storm problem with the additional RTS/CTS control packet exchanges. Inherently, communicating devices should adapt based on the dynamic vehicular network.

One of the most important factors that impacts network reliability is the interference level which is highly dependent on the transmission range for each communicating node. In this paper, we carefully study stop-and-go movement and incorporate an understanding of traffic waves onto the network design for one-hop periodic broadcast. Stop-and-go movement, a phenomenon that arises from a combination of shockwave and rarefaction waves, can occur in highways, especially during peak hours or when road incidents occur. Through analytical and simulation-based studies, we illustrate the coverage and packet reception rates performance measures for different traffic dynamics. Taking into consideration both reliability and interference minimization, we compare the performance for various transmission range adjustment schemes relative to the traffic stability.

II. RELATED WORKS

Our work is motivated by [1] which provides a first study to obtain the analytical lower-bound for the minimum transmission range in non-homogeneous distribution of vehicles in congested densities. Following this initial work, [2] uses a dynamic transmission-range assignment (DTRA) algorithm that employs transmission power control based on the relationship between connectivity and traffic density characteristics. Their approach is based on an analytical traffic flow model to estimate local density and derive vehicle trajectories using RoadSim to measure the performance of the communication system on several road configurations. The focus of their work and the DTRA algorithm is to adjust the transmission range by estimating local vehicle density and local traffic conditions (free flow versus congested traffic) without any prior message exchange with neighboring vehicles. In their work, the minimum transmission range is defined as an average maximum value of vehicle spacing for multi-lane case and the widest gap among vehicles for single-lane scenario. Further, to compensate for the non-homogeneous distribution of vehicles on a single-lane, the transmission range is increased by an additional constant that is proportional to length of the road of interest. Although their work achieves the goal of maintaining high connectivity, the communication issues such as collision due to the hidden and exposed terminal problems were not evaluated. An optimal adjustment in transmission range would improve communication by reducing wireless transmission collisions. Our work extends the dynamic transmission range by analyzing traffic dynamics on the road and incorporating traffic stability information as a relative measure to increase transmission range.

The work by [3] proposes the distributed fair power adjustment for vehicular networks (D-FPAV) algorithm that dynamically adjusts each vehicle's transmission power to prevent packet collisions. The optimization focuses on fairness of each communicating vehicle to receive and send safety information rather than network capacity, connectivity or coverage. Fairness in their adaptive transmission power scheme is validated through simulation results on a highway with different radio propagation models.

The work by [4] proposes an analytical model to evaluate the performance and reliability of safety-related services in DSRC systems on highways. The model considers several design metrics which include different safety-message priorities, the hidden terminal problem, transmission range, and contention window back-off mechanisms. From their analytical model, channel throughput, transmission delay, and packet reception rates were computed. The findings suggest that delay requirements can be met but high reliability cannot. The work by [5] provides extensive simulations to study the performance of one-hop broadcast beacon safety messages. Communication parameters used in the performance measures include transmission range, packet transmission interval, and message payload size.

The work by [6], [7] proposes an analytical model for connectivity in non-uniform traffic stream based on the Lighthill-Whitham-Richards (LWR) traffic flow model. The instantaneous connectivity factor is based the multi-hop broadcast communication and with different market penetration rates of DSRC-equipped vehicles. Further, connectivity can be computed as the traffic pattern evolves in a time-dependent manner. Theoretical results on the propagation distance for different transmission range values are shown for non-uniform traffic. The work by [8] proposes an analytical method to approximate connectivity for vehicular communication in highway under different traffic conditions as factors such as traffic density and vehicle velocity parameters can significant influence the performance of connectivity. Finally, [9] proposes to improve communication reliability with dynamic transmission range by incorporating fundamental traffic flow relationship. The work is focused on shockwave mobility pattern for multi-hop broadcast communication which is different from this paper.

III. TRAFFIC BEHAVIOR AND MODELING

This section describes the traffic scenario, vehicle movements and trajectories, and methodology to precisely compute vehicle locations and traffic stability in detail.

A. Traffic Scenarios

Our traffic scenario is a non-uniform congested traffic stream that covers a three kilometer unidirectional, one-lane highway network. We assume a critical density $\rho_c = 0.2\ \rho_j$ and a jam density of 150 veh/km. Further, we assume that every vehicle is DSRC-enabled (100% market penetration rate). Initially, the vehicles are randomly distributed within the three kilometer road segment with a condition that the distance between any two DSRC-enabled communications device is minimally 6.66 meters based on jam density value. Due to the non-uniform distribution of vehicles, there are instances of the road segment where the spacing between the forward and rear vehicle can be greater than the average vehicle spacing of the entire traffic stream for a given traffic density.

B. Car-Following Model

In traffic flow theory, various microscopic traffic models have been proposed such as Gibbs, General Motors, Pipes or the K-S car following models. In our traffic network, vehicles movement is based on Newell's car-following model for its simplicity. Furthermore, the accuracy of Newell's car-following model [10] has been compared with other microscopic car-following models [11], and have subsequently been verified with real highway results [12], [13].

The following formulation (1) describes Newell's car-following model in a congested road:

$$X_n(t+\tau) = X_{n-1}(t) - d \qquad (1)$$

where X_n and X_{n-1} are the following and leading vehicles' locations, respectively, d is the jam spacing of vehicle X_n, and τ is the time displacement of vehicle X_n. From the NG-SIM data [14], d and τ are set to 6.66 meters and 1 second, respectively. Hence, the nth vehicle trajectory will follow the trajectory of the (n-1)st vehicle as described in (1) for all vehicles on a congested road.

C. Vehicle Trajectories

Vehicle trajectories of stop-and-go waves for different congested traffic densities (from $\rho = 0.2\rho_j$ to $\rho = 0.9\rho_j$) of two minutes of driving time are computed in Figure 1. Increasing traffic density not only increases the number of vehicles on the road, but decreases vehicle speed which reduces spacing between vehicles. From the vehicle trajectories, we observe that all stop-and-go waves propagate backward as shown in Figures 1(a) to 1(h). As shown in those figures, as traffic density increases, more stop-and-go waves are created. However, when the traffic pattern is denser ($\rho > 0.5\rho_j$), these narrower stop-and-go waves start to merge into wider ones as shown in Figures 1(e) to 1(h).

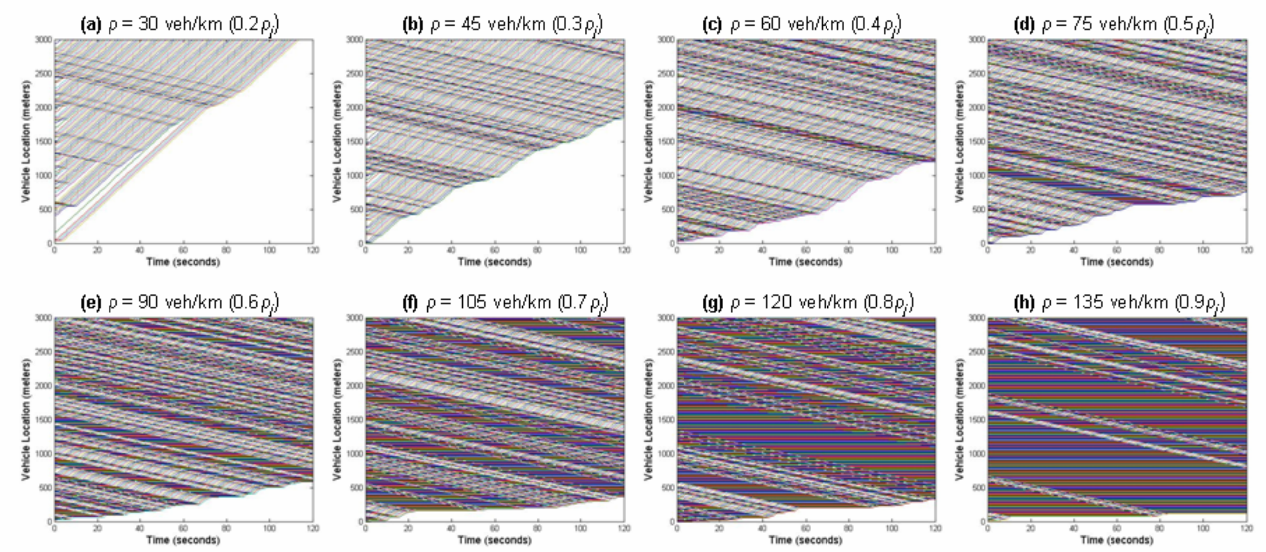

Figure 1. Vehicle Trajectories under Varying Densities

D. Traffic Dynamics

Using Newell's car-following model in III-B, the location of each individual vehicle on the road can be derived. By knowing the precise vehicle locations, the coefficient of variance (*CV*) of spacing for all vehicles in the traffic stream can be computed. Initially the *CV* is high due to the random vehicle distribution. In later time steps, as vehicles move according to Newell's car-following model, the *CV* of spacing decreases until it convergences to a fixed value. Figure 2 illustrates an example of *CV* adjustment (spacing) for different traffic densities. In comparison, the *CV* convergences much faster for higher density than with lower densities. For example, when $\rho > 60$ *veh/km* (0.5ρ_j) , the *CV* value converges within 10 seconds or less but with $\rho = 30$ *veh/km,* it took up to 40 seconds to converge and for the traffic stream to reach "stationary." At the stability point, most of the traffic stream is smooth except for a few specific points where the stop-and-go wave occurs. In general, higher traffic densities have a lower *CV* value to start (time *t=0)* since these higher traffic streams have less space to allow the formation of large gaps between vehicles.

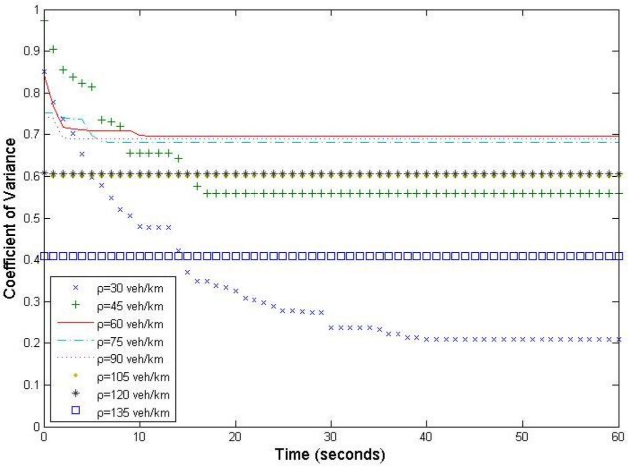

Figure 2. Evolution of the Coefficient of Variance with Random Initial Distribution of Vehicles

IV. NETWORK DESIGN

This section describes the mechanism in broadcasting and transmission range adjustment for improving the communication reliability.

A. Broadcasting

In vehicular networks, two scenarios that lead to the broadcast storm problem are multi-hop event-driven and single-hop periodic messages. In the former case, the issue occurs due to message flooding while in the latter case, periodic messaging (consecutive transmissions from the same sender) is problematic when the packet time elapse interval is short. In this work, we evaluate communication for safety applications on highways with single-hop periodic broadcast which include pre-crash sensing and cooperative adaptive cruise control applications.

B. Transmission Range Adjustment

Our proposed scheme adjusts the transmission range dynamically by taking traffic stability into consideration. The increase in transmission range is relative to *CV* to ensure a desirable coverage value for all nodes in the road network for a specific traffic pattern. The adjusted transmission range (TR_{adj}) can be computed using the following rule:

$$TR_{adj}(n) = (1 + n * CV) * TR_{avg\_sp} \qquad (2)$$

where n is the order of magnitude for increasing the coefficient of variance (*CV*) and TR_{avg_sp} is the average vehicle spacing over the entire traffic stream. When the traffic becomes uniform, *CV* is zero and TR_{adj} is the same as TR_{avg_sp}.

C. Coverage Model

In this section, we describe the model for measuring communication coverage in the vehicular network. Suppose

n vehicles travel in a road defined as $v_1, v_2, \cdots, v_n$, and the positions for all n vehicles are defined as $x_1, x_2, \cdots x_n$. Further, assume that v_1 is the leading vehicle of the traffic stream and v_{i+1} is the following vehicle for v_i, $\forall\, i = 1,2,\cdots,n-1$. Let the transmission range of vehicle i be denoted as R_i. Then the upstream and downstream coverage is defined by the following definition:

$$C_{i,upstream} = \begin{cases} 1/2 & \exists\, |x_i - x_j| \le R_i, \forall\, j = 1,2,\cdots,i-1 \\ 0 & ,otherwise \end{cases} \tag{3}$$

$$C_{i,downstream} = \begin{cases} 1/2 & \exists\, |x_i - x_k| \le R_i, \forall\, k = i+1,\cdots,n \\ 0 & ,otherwise \end{cases} \tag{4}$$

The coverage of each vehicle i is defined in terms of the Euclidean distance to the nearest upstream and downstream vehicles in the traffic stream:

$$C_i = C_{i,upstream} + C_{i,downstream} \tag{5}$$

The total coverage C of this vehicular network is denoted by:

$$C = \textstyle\sum_{i=1}^{n} C_i \,/n \tag{6}$$

D. Results and Discussion

Here, we illustrate the effects of traffic dynamics that range and density (from critical to jam density) on transmission range adjustment and coverage value defined earlier in sections IV-B and IV-C. Tables 1 and 2 provide details of the simulation runs of the analytical model for coverage with different transmission range adjustments. For higher fidelity in the results, the simulation was run 100 times with randomized traffic locations (with minimum 6.66 meters apart) for all vehicles and the average results are presented.

Table 1 shows the actual transmission range value increases according to equation (2). This adjustment value can be observed to be highly related by traffic stability. Comparing the two traffic patterns, we observe that the actual transmission range adjustment is greater in the initial randomized traffic. This is due to the fact that the coefficient of variance value is lower for stationary traffic using Newell's car-following model. Also, the transmission range differences between initial randomized and stationary traffic is less apparent in higher traffic densities.

As observed in Table 2, the increase in coverage is most apparent from $TR_{adj}(0)$ to $TR_{adj}(1)$ except when the traffic density is high such as $\rho = 0.9\ \rho_j$ and the traffic is near stationary to begin with. In order to achieve a 95% percentile in coverage in most cases, a transmission range adjustment of $TR_{adj}(2)$ and $TR_{adj}(3)$ is necessary for initial randomized traffic and stationary traffic.

We can see the impact of stop-and-go waves on traffic stability in the converged traffic scenario. In the $TR_{adj}(0)$ and $TR_{adj}(1)$ values, the coverage increase is consistent with higher traffic density. In addition, the coverage for a few traffic densities stay the same, in $\rho = 0.2\ \rho_j$ with $TR_{adj}(1)$ and thereafter, and in $\rho = 0.3\ \rho_j$ and $\rho = 0.4\ \rho_j$ with $TR_{adj}(2)$ and thereafter. When traffic density increases, the ratio between TR_{avg_sp} and "go" pattern spacing of the stop-and-go wave is greater and a larger transmission range adjustment of $TR_{adj}(3)$ is necessary to achieve a coverage value that approach 1.

V. SIMULATION ANALYSIS

A. Simulation Environment

We use the *ns*-2.33 network simulator to evaluate communication performance with the mobility model described in section III-C. For higher fidelity, we set configuration values according to the IEEE 802.11p standard draft and the main parameters used in the *ns*-2 simulation are presented in Table 3. To measure reliability of single-hop periodic broadcast, all nodes in the highway broadcast safety messages at 100 *ms* intervals for a duration of two seconds (an upper bound on human reaction time). The packet size is set to 382 bytes with 200 bytes of data payload, 128 bytes for a certificate, and 54 bytes for a signature, similar to [15]. The preferred data rate of 6 Mbps for vehicular safety applications is used which has the greatest benefit in overall reliability (in terms of packet reception rates) as confirmed by [16]. The simulation ran on a 2.3 GHz quad-core machine with 8 GB RAM and the multi-core processors provide speed up in the Monte Carlo simulations.

TABLE 3 COMMUNICATION CONFIGURATIONS

Parameters	**Values**
Antenna height	1.5 m
Antenna gain	1 dB
RxTh	-95 dBm
CSTh	-99 dBm
CPTh	4 dB
Data rate	6 Mbps
Frequency	5.9 GHz
Packet size	382 bytes
Transmission criteria	Single-hop periodic for all nodes in network
Message transmission interval	100 ms
Contention window size	15 slots (fixed)
Slot time	16 μs
Tx range (meters)	See table 1

B. Results and Discussion

For statistical reliability and to avoid correlation in the results, 100 independent runs (with varying seeds in *ns*-2) for each scenario are computed. Additional scripts were used to parse the raw output and compute performance measures. In particular, we evaluate the performance metric of packet reception rates (PRR) for all nodes. PRR is measured in the MAC level and is defined as the probability of receiving a packet sent within transmission distance.

TABLE 1. TRANSMISSION RANGE ADJUSTMENT (IN METERS)

	Initial Traffic (randomized)				Stationary Traffic (after convergence)			
density (veh/km)	$TR_{adj}(0)$	$TR_{adj}(1)$	$TR_{adj}(2)$	$TR_{adj}(3)$	$TR_{adj}(0)$	$TR_{adj}(1)$	$TR_{adj}(2)$	$TR_{adj}(3)$
$\rho = 0.2\rho_j$ (30)	33.333	60.556	87.779	115.001	33.333	40.282	47.231	54.180
$\rho = 0.3\rho_j$ (45)	22.222	39.569	56.916	74.263	22.222	34.377	46.531	58.686
$\rho = 0.4\rho_j$ (60)	16.667	29.286	41.905	54.525	16.667	27.710	38.753	49.795
$\rho = 0.5\rho_j$ (75)	13.333	23.300	33.266	43.232	13.333	22.756	32.180	41.603
$\rho = 0.6\rho_j$ (90)	11.111	19.067	27.022	34.977	11.111	18.874	26.637	34.400
$\rho = 0.7\rho_j$ (105)	9.524	15.794	22.064	28.334	9.524	15.733	21.941	28.150
$\rho = 0.8\rho_j$ (120)	8.333	13.027	17.721	22.415	8.333	13.006	17.679	22.351
$\rho = 0.9\rho_j$ (135)	7.407	10.463	13.519	16.575	7.407	10.461	13.514	16.567

TABLE 2. NETWORK COVERAGE

	Initial Traffic (randomized)				Stationary Traffic (after convergence)			
density (veh/km)	$TR_{adj}(0)$	$TR_{adj}(1)$	$TR_{adj}(2)$	$TR_{adj}(3)$	$TR_{adj}(0)$	$TR_{adj}(1)$	$TR_{adj}(2)$	$TR_{adj}(3)$
$\rho = 0.2\rho_j$ (30)	0.644	0.900	0.944	0.978	0.122	0.989	0.989	0.989
$\rho = 0.3\rho_j$ (45)	0.607	0.852	0.941	0.970	0.474	0.644	0.993	0.993
$\rho = 0.4\rho_j$ (60)	0.633	0.861	0.956	0.967	0.594	0.783	0.994	0.994
$\rho = 0.5\rho_j$ (75)	0.689	0.862	0.951	0.978	0.667	0.813	0.889	0.996
$\rho = 0.6\rho_j$ (90)	0.733	0.863	0.948	0.974	0.719	0.841	0.922	0.967
$\rho = 0.7\rho_j$ (105)	0.737	0.863	0.937	0.962	0.737	0.863	0.937	0.959
$\rho = 0.8\rho_j$ (120)	0.819	0.903	0.944	0.972	0.819	0.897	0.939	0.967
$\rho = 0.9\rho_j$ (135)	0.904	0.943	0.960	0.983	0.904	0.941	0.958	0.978

To calculate the probability of packet reception with the corresponding transmission range adjustment, our analysis on reliability is based on a weighted packet reception rate that multiplies the PRR and coverage. Figures 3 and 4 illustrate the performance measures for initial traffic and stationary traffic which exhibit the stop-and-go waves. For both Figures 3 and 4, a 70% packet reception rate with coverage is achieved in the optimal case.

In Figure 3, the packet reception rate with coverage is consistence with a higher transmission range adjustment. Further, $TR_{adj}(2)$ and $TR_{adj}(3)$ have similar results for all traffic densities. Actual selection of $TR_{adj}(2)$ and $TR_{adj}(3)$ is dependent on the network design criteria and whether higher reliability or higher coverage is more important.

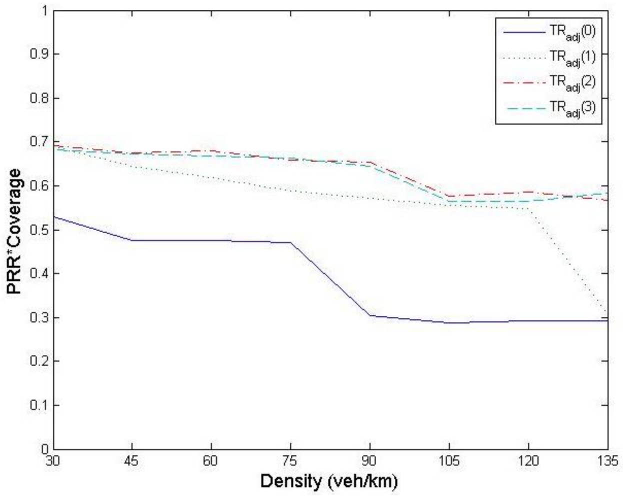

Figure 3. PRR with Coverage for Initial Randomized Traffic

Figure 4 indicates a large difference in packet reception rate with coverage. For small and large traffic densities, $TR_{adj}(2)$ performed better, while moderate congested traffic, $TR_{adj}(3)$ showed better results. This is because there are more stop-and-go patterns in the moderate congested traffic, as previously shown in Figures 1(d) and 1(e).

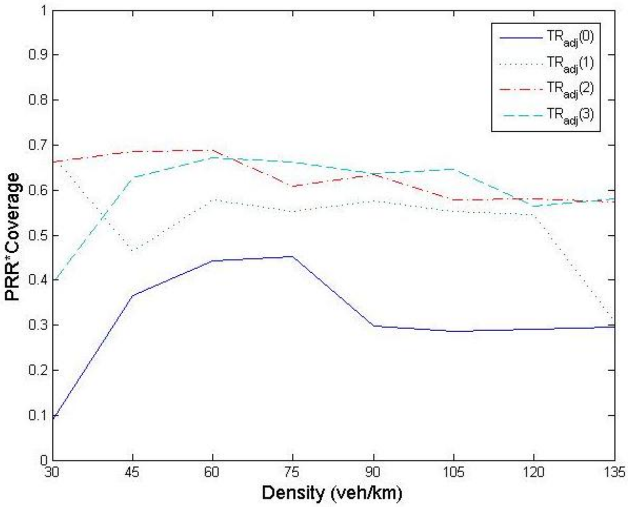

Figure 4. PRR with Coverage for Stationary Traffic

VI. CONCLUSION

Deploying successful large scale VANETs hinges on the ability of these systems to guarantee message delivery. In this work, we examine the performance of broadcast communication and seek to improve its reliability with dynamic transmission range adjustment. In particular, we analyze traffic dynamics as a result of stop-and-go waves for varying traffic densities.

Longer transmission range allows for more receiving nodes but at the expense of higher interference. Our evaluation of dynamic transmission range adjustment includes an analytical study of coverage and simulation study of packet reception rates using *ns*-2. Based on our observation, we see that the near optimal transmission range adjustment with traffic stability consideration is near two to three times the coefficient of variance. Moreover, a stop-and-go traffic pattern can impact the transmission range adjustment decision, depending on traffic density.

For future work, mixed traffic can be considered with different vehicle types, time displacement values, and multi-lane highway scenarios. To study how traffic should inform network design in large scale vehicular networks, macroscopic traffic model can be used. In addition, a multi-layer networking model that involves both the upper (application) and lower (network) layers for wireless broadcast should be investigated and designed for future inter-vehicle communication systems.

VII. ACKNOWLEDGMENT

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