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*.

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

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.

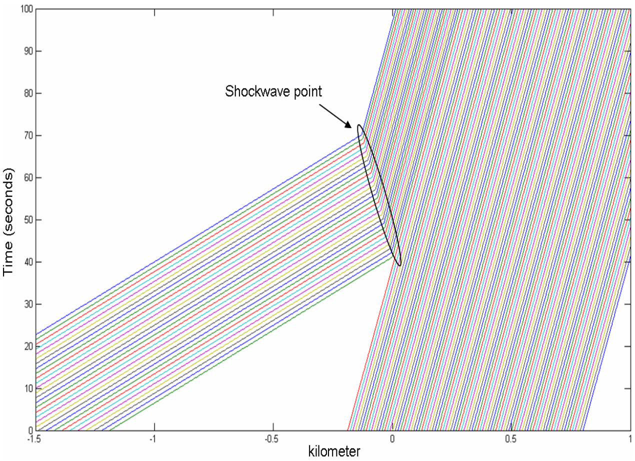

Figure 1. Trajectory of Shockwave Traffic

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)*.

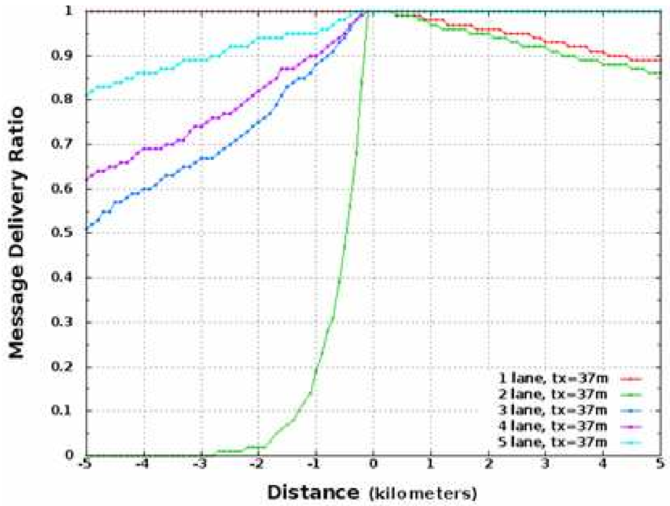

Figure 2. Message Delivery Ratio for Fixed Transmission Range

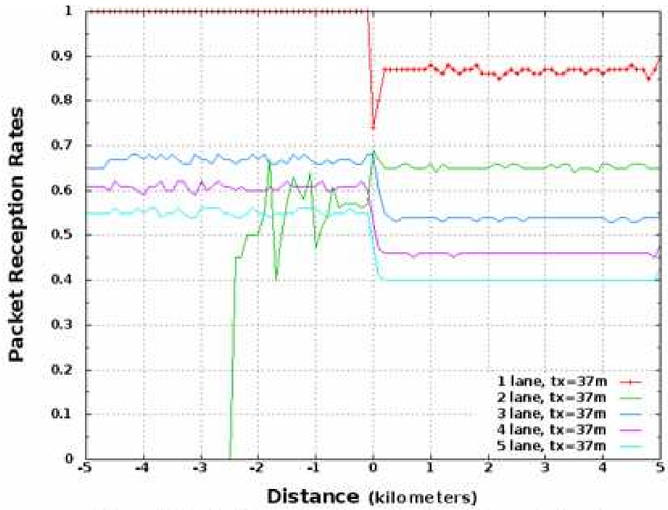

Figure 3. Packet Reception Rates for Fixed Transmission Range

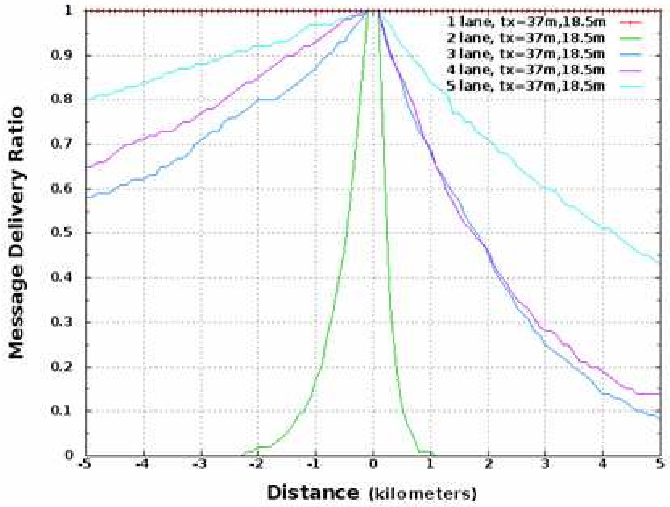

Figure 4. Message Delivery Ratio for Dynamic Transmission Range

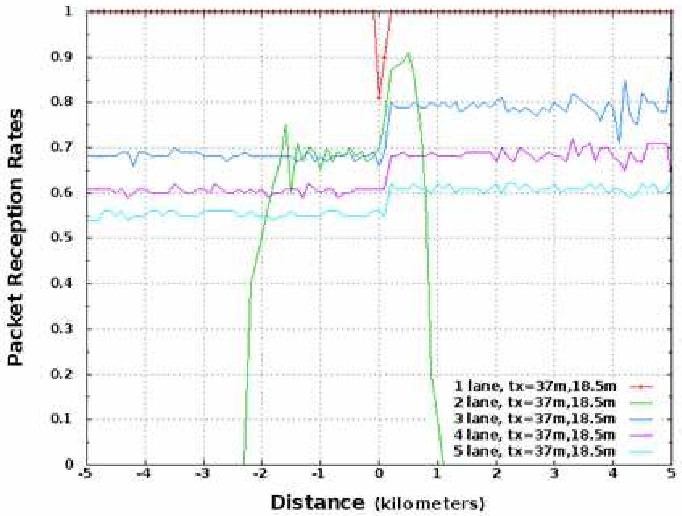

Figure 5. Packet Reception Rates for Dynamic Transmission Range

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

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

This research is supported in part by a grant from University of California Transportation Center. We would like to thank Hao Yang for assistance in the shockwave mobility and to Jaeyoung Jung and Dr. Jay Jayakrishnan for their discussions.

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