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).

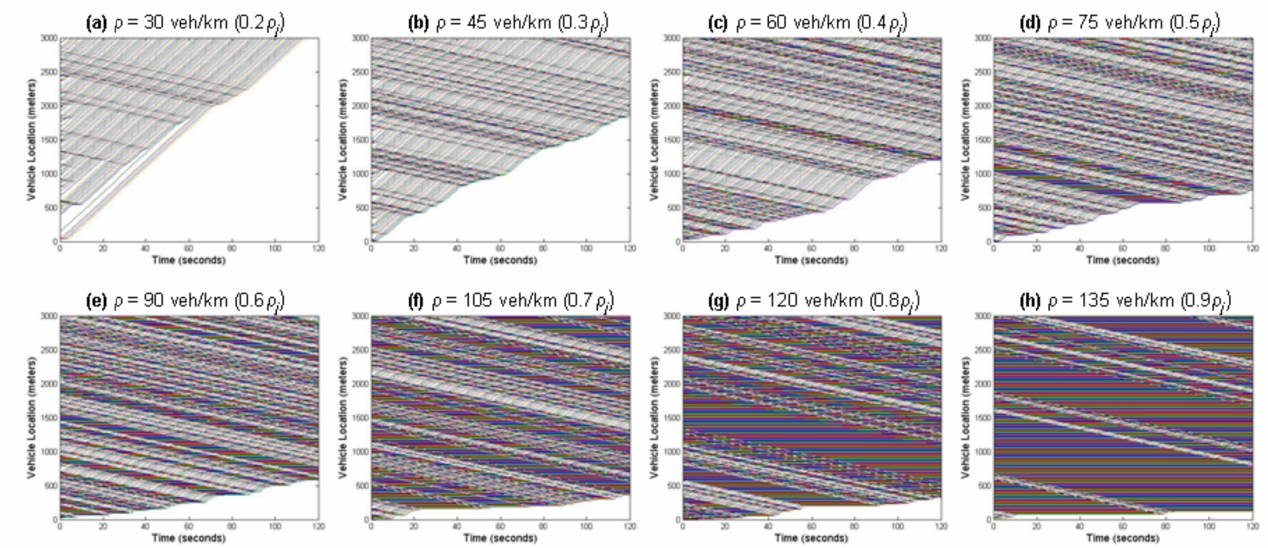

Figure 1. Vehicle Trajectories under Varying Densities

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* ($0.5\rho_j$) , 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.

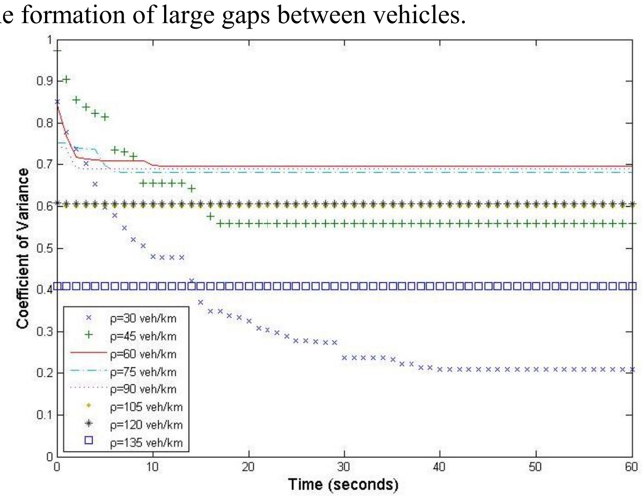

Figure 2. Evolution of the Coefficient of Variance with Random Initial Distribution of Vehicles

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:

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

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

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:

$$C_i = C_{i,upstream} + C_{i,downstream} \quad (5)$$

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

$$C = \sum_{i=1}^{n} C_i \,/ n \quad (6)$$

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.

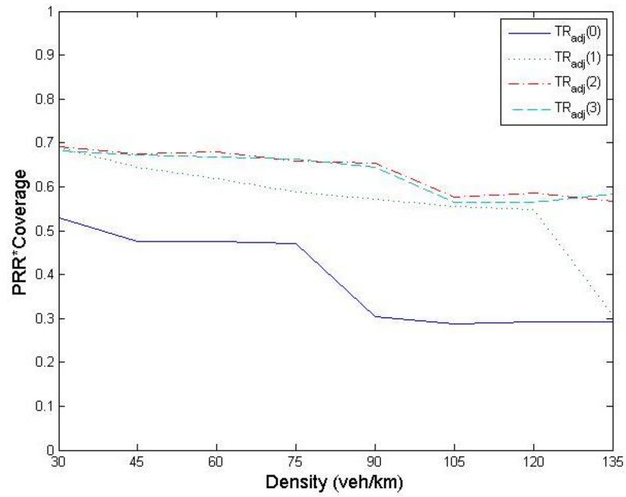

Figure 3. PRR with Coverage for Initial Randomized Traffic

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).

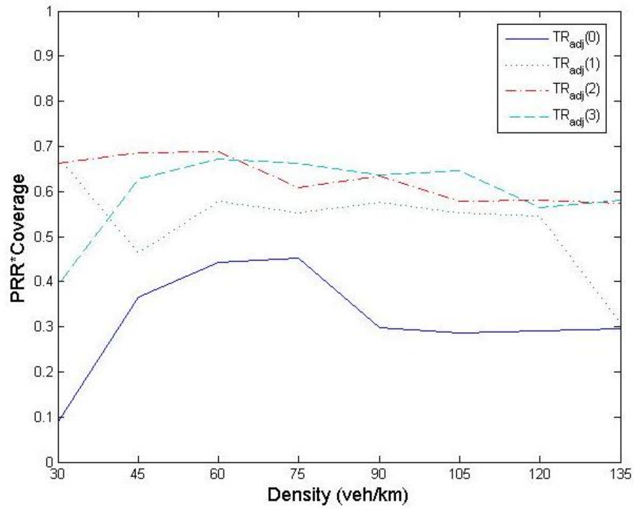

Figure 4. PRR with Coverage for Stationary Traffic

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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