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 show that 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 pattern 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 proliferation of navigation systems and the ability to retrieve real-time information on positioning and traffic conditions are improving the experience of millions of vehicle drivers. Advanced telematic systems will only continue to grow with 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 Vehicular Ad Hoc Networks (VANETs), 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 which depends 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 to the dynamics of the 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 into 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 stop-and-go traffic dynamics. Taking into consideration both reliability and interference minimization, we compare the performance for various transmission range adjustment schemes relative to the stop-and-go movement based on the coefficient of variation for the traffic pattern.

II. RELATED WORKS

Our work is motivated by [1] which provides an early study to obtain the analytical lower-bound for the minimum transmission range in non-homogeneous distribution of vehicles in congested densities. Following this work, [2] uses a dynamic transmission-range assignment (DTRA) algorithm that employs transmission power control based on 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. 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. Although their work maintains high connectivity, 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 pattern as a relative measure to increasing 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 on 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 significantly influence the performance of connectivity. Finally, [9] proposes to improve communication reliability with dynamic transmission range by incorporating fundamental traffic flow relationships. The work is focused on shockwave mobility patterns 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 pattern in detail.

A. Traffic Scenarios

Our traffic scenario is a non-uniform congested traffic stream that covers a three kilometer unidirectional, one-lane highway. The three kilometer distance is a ring road where vehicles do not leave or enter the road and the stop-and-go pattern emerges and persists over time. We set a critical density \( \rho_c = 0.185 \rho_p \) and a jam density of 150 veh/km. Further, we assume that every vehicle is DSRC-enabled. Initially, the vehicles are randomly distributed within the three kilometer road segment with a condition that the distance between any two vehicles is minimally 6.66 meters based on jam density value. Due to the non-uniform distribution, the spacing between any leading and following vehicles can be greater or smaller than the average vehicle spacing for a given traffic density.

B. Car-Following Model

In traffic flow theory, various microscopic traffic models have been proposed such as Pipes, General Motors, or Gipps car following models. In our traffic network, vehicles movement is based on Newell-Daganzo car-following model for its simplicity. Furthermore, the accuracy of Newell-Daganzo method [10], [11] has been compared with other microscopic car-following models [12] and subsequently verified with real highway results [13], [14].

The following formulation (1) describes Newell-Daganzo car-following model for a congested road:

\[
X_n(t + \tau) = \min \{ X_{n-1}(t) - d, X_n(t) + V_f \cdot \tau \}
\]

where \( X_n \) and \( X_{n-1} \) are the following and leading vehicles’ locations, respectively, \( d \) is the jam spacing of vehicle \( X_n \), free flow speed \( V_f = 65 \text{ mph} \), and \( \tau \) is the time gap of vehicle \( X_n \). Further, \( d \) and \( \tau \) are set to 6.66 meters and 1 second, respectively. Hence, the \( n \)th 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 \( \rho = 0.2 \rho_p \) to \( \rho = 0.9 \rho_p \)) 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 with reduced 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 (\( \rho > 0.5 \rho_p \)), these narrower stop-and-go waves start to merge into wider ones as shown in Figures 1(e) to 1(h).
D. Traffic Dynamics

Using Newell-Daganzo 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 variation ($CV$) 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-Daganzo car-following model, the $CV$ of spacing decreases until it converges to a fixed value. Figure 2 illustrates an example of $CV$ adjustment (spacing) for different traffic densities.

IV. NETWORK DESIGN

This section describes the mechanism for transmission range adjustment to improve broadcast reliability.

A. Broadcasting

In vehicular networks, two common 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 with shorter inter-message time as a result of high message generation rate. 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 pattern 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:

$$ TR_{adj} (m) = (1 + m \cdot CV) \cdot TR_{avg, sp} $$

(2)

where $m$ is the order of magnitude for increasing the coefficient of variation ($CV$) 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:

\[
C_{i, \text{upstream}} = \begin{cases} \frac{1}{2}, & \exists |x_i - x_j| \leq R_i, \forall j = 1, 2, \cdots, i - 1 \\ 0, & \text{otherwise} \end{cases} \tag{3}
\]

\[
C_{i, \text{downstream}} = \begin{cases} \frac{1}{2}, & \exists |x_i - x_k| \leq R_i, \forall k = i + 1, \cdots, n \\ 0, & \text{otherwise} \end{cases} \tag{4}
\]

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:

\[
C_i = C_{i, \text{upstream}} + C_{i, \text{downstream}} \tag{5}
\]

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

\[
C = \sum_{i=1}^{n} C_i / n \tag{6}
\]

D. Results and Discussion

Here, we illustrate the effects of traffic dynamics on transmission range, coverage, and density values defined earlier in sections IV-B and IV-C.

Figure 3 shows the communication coverage for different traffic densities (from \( \rho = 0.2\rho_i \) to \( \rho = 0.5\rho_i \)) and transmission range adjustment (from \( TR_{adj}(0) \) to \( TR_{adj}(3) \) ) over time as traffic pattern moves from random to stationary.

![Figure 3. Evolution of Coverage over Time](image)

When the density is lower (\( \rho = 30 \text{ veh/km} \) and \( \rho = 45 \text{ veh/km} \)), we observe that coverage degrades over time as the formation of stop-and-go traffic create larger gaps that are longer than the transmission range of \( TR_{adj}(0) \). In the higher density case (\( \rho = 60 \text{ veh/km} \) and \( \rho = 75 \text{ veh/km} \)), coverage converges to a fixed value as traffic becomes stationary over time.

From Figure 3, we observe that a one to two order of magnitude increase in transmission range can have significant impact on coverage. Further, 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. Finally, for all cases a transmission range adjustment of \( TR_{adj}(3) \) is necessary to achieve a coverage value that approaches 1.

Figure 4 provides an illustration of vehicle spacing over time for a single instance of a vehicle following another vehicle on the highway. As the figure shows, lower density tends to have longer constant spacing. In the higher density case, there is greater number of fluctuation but with smaller spacing differences. The results validate the coverage values in Figure 3 for various transmission range adjustment values under different traffic densities.

![Figure 4. Evolution of Vehicle Spacing over Time](image)

Tables 1 and 2 illustrate the actual transmission range value increases according to equation (2). For higher fidelity in the results, the transmission range increase is based on simulation run of 100 times with randomized traffic locations (with minimum 6.66 meters apart) for all vehicles and the average mobility results are presented.

This adjustment value can be observed as highly related to traffic patterns. Comparing the two traffic conditions, 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 variation value is lower for stationary traffic using Newell-Daganzo car-following
model. Also, the transmission range differences between initial randomized and stationary traffic is less apparent in higher traffic densities.

**TABLE 1** TRANSMISSION RANGE ADJUSTMENT FOR INITIAL TRAFFIC

<table>
<thead>
<tr>
<th>Randomized Vehicle Location (in meters)</th>
<th>( TR_{\text{adj}} (m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (veh/km)</td>
<td>( m = 0 )</td>
</tr>
<tr>
<td>30</td>
<td>33.3</td>
</tr>
<tr>
<td>45</td>
<td>22.2</td>
</tr>
<tr>
<td>60</td>
<td>16.7</td>
</tr>
<tr>
<td>75</td>
<td>13.3</td>
</tr>
<tr>
<td>90</td>
<td>11.1</td>
</tr>
<tr>
<td>105</td>
<td>9.5</td>
</tr>
<tr>
<td>120</td>
<td>8.3</td>
</tr>
<tr>
<td>135</td>
<td>7.4</td>
</tr>
</tbody>
</table>

**TABLE 2** TRANSMISSION RANGE ADJUSTMENT FOR STATIONARY TRAFFIC

<table>
<thead>
<tr>
<th>Vehicle Location after Convergence (in meters)</th>
<th>( TR_{\text{adj}} (m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (veh/km)</td>
<td>( m = 0 )</td>
</tr>
<tr>
<td>30</td>
<td>33.3</td>
</tr>
<tr>
<td>45</td>
<td>22.2</td>
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<tr>
<td>60</td>
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<tr>
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<tr>
<td>90</td>
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<td>8.3</td>
</tr>
<tr>
<td>135</td>
<td>7.4</td>
</tr>
</tbody>
</table>

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.

**TABLE 3** COMMUNICATION CONFIGURATIONS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna height</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>1 dB</td>
</tr>
<tr>
<td>RxTh</td>
<td>-95 dBm</td>
</tr>
<tr>
<td>CSTh</td>
<td>-99 dBm</td>
</tr>
<tr>
<td>CPTh</td>
<td>4 dB</td>
</tr>
<tr>
<td>Data rate</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>Frequency</td>
<td>5.9 GHz</td>
</tr>
<tr>
<td>Packet size</td>
<td>382 bytes</td>
</tr>
<tr>
<td>Transmission criteria</td>
<td>Single-hop periodic for all nodes in network</td>
</tr>
<tr>
<td>Message transmission interval</td>
<td>100 ms</td>
</tr>
<tr>
<td>Contention window size</td>
<td>15 slots (fixed)</td>
</tr>
<tr>
<td>Slot time</td>
<td>16 µs</td>
</tr>
<tr>
<td>Tx range (meters)</td>
<td>See table 1 and table 2</td>
</tr>
</tbody>
</table>

To measure reliability of single-hop periodic broadcast, all nodes on 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].

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.

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 5 and 6 illustrate the performance measures for initial traffic and stationary traffic which exhibit the stop-and-go waves. An optimal value of 70% PRR with coverage is achieved.

In Figure 5, the packet reception rate with coverage is consistency with a higher transmission range adjustment. For traffic densities 75 veh/km or lower, the optimal delivery ratio is between \( TR_{\text{adj}} (2) \) and \( TR_{\text{adj}} (3) \) and the consistently of increasing and decreasing trend is observed. For higher traffic densities, the delivery ratio significantly increases from \( TR_{\text{adj}} (0) \) to \( TR_{\text{adj}} (1) \) as it shows that a larger transmission range adjustment is desired.

**Figure 5.** PRR with Coverage for Initial Randomized Traffic

Figure 6 indicates a large difference in packet reception rate with coverage. For small traffic densities, \( TR_{\text{adj}} (2) \) performed better, while \( TR_{\text{adj}} (3) \) and \( TR_{\text{adj}} (4) \) showed the best results for moderate and highly congested traffic. This is
because there are more stop-and-go patterns at the higher traffic densities, as shown earlier in Figures 1(d) and 1(e).

Figure 6. PRR with Coverage for Stationary Traffic

In order to estimate the efficiency of our approach, we also ran experiments comparing the benefits of dynamic transmission range as a metric of traffic pattern compared with fixed transmission range and the earlier method used by DTRA. Overall we observe that in lower traffic densities, the instability of traffic flow has a bigger impact in vehicle spacing. Hence, our method performed better in comparison with the other approaches. The results for these are not shown due to spacing constraint.

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, the near optimal transmission range adjustment with stop-and-go traffic waves is about two to three times the coefficient of variation for lower traffic densities. 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 gap 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.

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REFERENCES


