Parameters that Affect Safety Message Delay in Sparse Infrastructure-less Vehicular Networks

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***Abstract*—In sparse highway vehicular networks, the high probability for network disconnection at the initial stages of introducing the DSRC technology can be mitigated by the deployment of fixed infrastructure points known as Road Side Units (RSU). However, due to the cost associated with the deployment and maintenance of significant numbers of RSUs, it is highly unlikely that the majority of highways will be seeing RSU support in the near future.**

In this paper we study the impact of specific vehicular network parameters in the communication delays in infrastructure-less highway scenarios: first, the deceleration of vehicles, and consequently, a decrease in their separation from succeeding vehicles; and second, the transmission power of the IEEE 802.11p radio, which can be increased to achieve faster connectivity with the succeeding vehicle. Our results show that the connectivity of sparse vehicular networks can be improved substantially by varying these parameters.

I. Introduction

Vehicular networks in highway scenarios must often operate as delay-tolerant networks, as a consequence of low traffic density during certain hours of the day [1]. The sparsity of such networks causes frequent node disconnection, while high re-healing times push the delays associated with the propagation of safety messages to tens and hundreds of seconds. This affects the network's ability to react to emergencies, by alerting drivers and diverting traffic.

To improve the network's re-healing time and speed up the broadcast of safety messages, Road Side Units (RSUs) can be deployed, either in a standalone fashion (disconnected RSUs), or connected to a roadside backbone network (connected RSUs). Previous work has shown that, in highways, connected RSUs can substantially improve the network, while disconnected RSUs, although cheaper, yield very modest gains [2], [3]. However, the cost of such an infrastructure deployment is oftentimes prohibitive, and it is unlikely that all but a small portion of the world's highways will see RSU installations in the near future.

One approach to improve re-healing time in infrastructure-less roads is to have vehicles acting as self-organizing nodes and mobile RSUs, *i.e.*, having vehicles perform the functionality of deployed RSUs. However, the impact of the vehicular network parameters on the communication, and how these parameters can be tuned to allow the nodes to act as RSUs, is unclear.

This approach draws its inspiration from self-organizing biological systems such as ant colonies, schools of fish, and swarms of birds whereby the colony can take care of several key functions through the co-operation of its members. The idea of using biologically inspired approaches in transportation problems has been approached by previous works in vehicular research [4]–[6] – this powerful approach holds the promise of solving several acute transportation problems.

In this paper, we show that vehicles in a sparse network, under the right conditions, can act as mobile RSUs, thus obviating the need for deployment of RSUs which is an expensive proposition. But the vehicle's mobility, lack of backbone access, and a general need to not impact each driver's freedom of movement should be carefully considered to see if one can apply the aforementioned approach to develop vehicular networks with a reduced number of RSUs.

The aim of this paper is to discuss and evaluate vehicular network parameters that can introduce significant impact in highway vehicular networks with no infrastructure support, with the purpose of reducing message transmission delays. We consider improvements that can be brought by the change of the following parameters:

- Deceleration of vehicles in the accident lane, to speed up the approach by rear disconnected vehicles, which is feasible as long as the deceleration is not abrupt and the vehicle can move to an emergency lane.
- Power control (by the means of range boosting) at the head and tail vehicles of each cluster, increasing the vehicles' transmission range in case of a disconnection, which is feasible if the transmission power is kept under the IEEE 802.11p maximum of 44.8 dBm EIRP (Effective Isotropic Radiated Power).

To this end, we first outline an analytical model for the one-way traffic scenarios (based on the characteristic exponential distribution of vehicles on highways [1]); then, we perform comprehensive Monte Carlo simulations of highway traffic where an accident has occurred, with the deceleration and range boosting techniques applied. We study the re-healing time of an emergency message, which is the time it takes for a message originating at the accident to reach other disconnected vehicles approaching the accident location, for both one-way traffic and two-way traffic scenarios.

The impact on re-healing time caused by the deceleration and the range boosting techniques is first evaluated separately, for different levels of deceleration and range boosting, and then jointly, with both techniques applied simultaneously. The results show that the impact of these parameters can vary substantially, and depends heavily on the traffic density and the presence (or absence) of opposite lane traffic.

The remainder of this paper is organized as follows. An overview of the related work on techniques for emergency broadcasts in highway vehicular networks is presented in Section II. Section III introduces an analytical model to determine the broadcast delay of safety messages when deceleration and range boosting techniques are applied. Details on our Monte Carlo simulation platform, simulation results, and comparisons with analytical models are given in Section IV and discussed in Section V. Finally, concluding remarks are presented in Section VI, along with directions for future work.

II. Related Work

Research in vehicular ad hoc networks is maturing, with a significant body of work on the main architecture and protocols for vehicular networks now readily available. The focus on the performance of such networks in areas of low vehicle density, however, has been relatively sparse, with most works focusing on well-connected scenarios. The broadcast of emergency messages, and techniques to decrease the time that these messages take to reach their intended destinations, is an important design consideration for any safety-oriented vehicular network.

The dynamics of two-way highway traffic have been studied in previous works such as [1] and [7], where message delivery delay is analyzed in the context of a low-density, sparse network. A more generic analytical model for the propagation of delay-tolerant messages in vehicular networks is presented in [8], with considerations for vehicle density, speed, and radio range. In [9], the dynamics of emergency message dissemination in multi-hop vehicular networks are analyzed under probabilistic channel models that account for interference, and broadcast schemes tailored to the minimization of message delay in these networks have been proposed in other works such as [10]–[12]

Interference and packet collisions in vehicular networks can also lead to failures in the reception of safety-critical messages. The work in [13] proposes a distributed power control scheme to limit the load of periodic messages on the network and secure bandwidth for emergency broadcasts. In [14], a distributed MAC scheme with strict priority requirements for emergency messages is proposed as an alternative to previous statistical-based priority MAC schemes, reducing the node-to-node propagation delay. In [15], a cross-layer approach is proposed to address the same reliability issue, with a relay selection mechanism that jointly integrates geographical location, vehicle speed and physical layer data in the decision process. A broadcast control mechanism specifically tailored for emergency warning packets is also shown in [16], where the criteria for rebroadcasting safety messages is dynamically adapted to the number of neighbors of each vehicle. In the framework of emergency message dissemination, [17] suggests segmenting the vehicles in range of the message source, delegating the forwarding duty to a single vehicle and thereby reducing broadcast delay. Most of these studies are focused on the performance of the broadcast medium and the reliability of safety messages.

In this work, we propose new mechanisms to reduce message broadcasting delay that are inspired by self-organizing biological systems, and that are applicable in scenarios where deployments of Road Side Units are not possible or feasible. We study the delay for an emergency message to be broadcast across a segment of road (Region of Interest) to vehicles that are not in the immediate vicinity of the accident, with techniques that can be used to reduce that delay without introducing additional infrastructure on the road.

III. Analytical Models and Simulation Platform

In this section we outline the key steps of an analytical framework that characterizes the expected re-healing time in a single lane scenario. This section presents the analytical models for studying the effects of braking and range boosting, which we then use in Section IV to validate our simulation results.

The density of sparse traffic in highway scenarios has been shown to follow an exponential distribution [1]. The framework is designed with the assumption that vehicles travel at fixed speeds – this is an approximation for sparse highway traffic that previous research has found to be realistic and to not cause meaningful loss of statistical significance [1], [2].

Given a fixed radio transmission range R, in meters, and a road traffic density λ, in vehicles per meter, we define clusters as *groups of vehicles that can communicate with one another through a single- or multi-hop path*. For the purpose of studying the effects of tail vehicle range boosting, a second range variable, R_b, is introduced. When range boosting is applied, R_b is increased to the desired range for the tail vehicle; otherwise, $R_b = R$. It is assumed that the network can identify which vehicle in a cluster is the tail vehicle, which is trivial through GPS positioning, but also possible through existing protocols [18].

When the tail vehicle in a cluster begins decelerating, it will connect with the lead vehicle from the following cluster when the vehicles reach a distance of R_b. With the frame of reference centered on the tail vehicle, the preceding vehicle has a zero relative speed (as it travels at the same speed as the braking vehicle), and will be accelerating towards the tail vehicle as that vehicle decelerates. The distance that must be traveled by that vehicle before communication is established is given by $s_{inter} - R_b$, where s_{inter} represents the distance between clusters (inter-cluster spacing, see [1]).

We assume that the deceleration of a vehicle is constant up to the point where the vehicle stops. From the point of view of the decelerating vehicle A, the next vehicle's speed is initially zero (it follows A at the same speed); then, as A decelerates, the next vehicle's speed towards it increases linearly; and when A reaches a full stop, the next vehicle will be approaching A at its full, constant speed.

Consider a vehicle's braking acceleration to be a_b, each vehicle's top speed v, and an arbitrary distance X between two disconnected vehicles ($X > R_b$). Using elementary equations of motion, one can determine the time for the vehicles to connect as the forward vehicle begins to decelerate:

$$\text{delay} = \begin{cases} \sqrt{2(X - R_b)a_b{}^{-1}} & \text{if } X - R_b < \frac{v^2}{2a_b} \\ \frac{v}{a_b} + (X - R_b - \frac{v^2}{2a_b})\frac{1}{v} & \text{if } X - R_b \geq \frac{v^2}{2a_b} \end{cases} \quad (1)$$

One can now calculate the expected delay, $E[Tr_A]$, when the vehicles are exponentially distributed and their inter-cluster distance is S_{inter}. From eq. (1), one can first obtain the probability P_A for $X - R_b < \frac{v^2}{2a_b}$, and then the delays $E[Tr_A^1]$ (from the top piece of eq. (1)) and $E[Tr_A^2]$ (from the bottom piece of eq. (1)).

The probability P_A that the vehicles will connect before the braking vehicle comes to a full stop is given by

$$P_A = P\left[S_{inter} - R_b < \frac{v^2}{2a_b}\right] = e^{\lambda\left(R - \frac{v^2 + 2a_b R_b}{2a_b}\right)} \quad (2)$$

The expected inter-cluster spacing that will lead to the vehicles connecting before full stop is given by

$$\begin{aligned} E[S_{inter}|S_{inter} < \kappa] &= \int_R^\kappa s_{inter} \cdot \frac{f_{S_{inter}}(s_{inter})}{F_{S_{inter}}(\kappa)} \mathrm{d}s_{inter} \\ &= \frac{\kappa - R}{e^{\lambda(R-\kappa)} - 1} + \frac{1}{\lambda} + \kappa \end{aligned} \quad (3)$$

where $\kappa = \frac{v^2}{2a_b} + R_b$. The delay, from eqs. (1-top) and (3), will be:

$$E[Tr_A^1] = \sqrt{2E\left[S_{inter}|S_{inter} < \kappa\right] a_b{}^{-1}} \quad (4)$$

If the vehicles only connect after the braking vehicle comes to a full stop, both the time when the vehicle is decelerating and the time when the vehicle is stopped must be considered. This case occurs when inter-cluster spacing S_{inter} is greater than $v^2/2a_b + R_b$:

$$\begin{aligned} E[S_{inter}|S_{inter} \geq \kappa] &= \int_\kappa^\infty s_{inter} \cdot \frac{f_{S_{inter}}(s_{inter})}{1 - F_{S_{inter}}(\kappa)} \mathrm{d}s_{inter} \\ &= \kappa + \frac{1}{\lambda} \end{aligned} \quad (5)$$

The resulting delay, from eqs. (1-bottom) and (5), will be:

$$E[Tr_A^2] = \frac{v}{a_b} + \left(E\left[S_{inter}|S_{inter} \geq \kappa\right] - \frac{v^2}{2a_b}\right) \cdot \frac{1}{v} \quad (6)$$

Combining the two cases from (4) and (6), and their associated probabilities from (2), one can obtain the expected re-healing time $E[Tr_A]$:

$$E[Tr_A] = P_A \cdot E[Tr_A^1] + (1 - P_A) \cdot E[Tr_A^2]$$

This re-healing time, $E[Tr_A]$, is the delay from one cluster to the next. In order to determine the time to reach a vehicle that is d meters away from the source (such as the 10 km re-healing time, which is our reference metric in Sec IV), one must first determine how many gaps exist between the source and the destination vehicles. Given the distance d between both vehicles, computing the mean number of gaps (G_C) from the cluster length (C_L) and intercluster spacing (S_{inter}) is straightforward:

$$G_C(d) = \frac{d}{E[C_L] + E[S_{inter}]} \quad (7)$$

The cluster length and intercluster spacing distributions can also be derived from the exponential distribution of vehicles in a straightforward way [1]. The mean re-healing time involving multiple gaps can be determined by multiplying the *Gap Count* G_C with the per-gap re-healing time, $E[Tr_A]$.

The methodology presented here for one-way traffic can be applied similarly to a statistical two-lane model, such as the one in [1], to obtain a model suitable for analysis of two-way traffic.

IV. Effects of Deceleration and Power Control in Re-healing Time

In this section we present the results of our simulation platform and analytical models, and show how deceleration and range boosting can improve re-healing time in sparse vehicular networks. We consider both scenarios where two-way traffic exists (typical with highways) and where only one-way traffic is present.

A. Monte Carlo Simulation Model

Our network simulations are built on top of NS3 [19], and implement a two-lane highway where traffic can flow in one or two directions. The vehicle generation routine inserts vehicles at the start of the lane following the exponential distribution, with definable density. An accident can be generated, blocking the road and causing vehicles in the same lane of the accident to form a dense queue behind it.

As was explained in Sec. III, vehicles move at a constant speed, and there is no overtaking. Each vehicle is equipped with a radio device, and for two-way traffic scenarios, the vehicles in the lane opposite to the accident are capable of performing *Store-Carry-Forward*, where a vehicle can hold an emergency message until it is in reach of another vehicle.

Upon receiving an emergency message, vehicles are instructed to broadcast it to all neighbors. The transmission range of vehicles is set to 250 m, and can be dynamically controlled for the range boosting scenarios.

Each simulation begins by allowing time for the road to fill with vehicles. Then, the accident is triggered at the specified location, broadcasting a message, and the time for that message to reach another vehicle that is 10 km away from the accident is registered. For statistical significance, each data point is averaged over a minimum of 100 repetitions, and 95% confidence intervals are generated to ensure that sufficient repetitions are performed.

Our reference performance metric for emergency message broadcasts is a 10 km re-healing time: the time it takes for an emergency message to reach a vehicle that is 10 km away from the point of origin, in the lane of interest. The re-healing time is the most crucial metric in emergency broadcast, as the goal is to reach vehicles approaching the emergency site so drivers can quickly be made aware of the emergency. From a traffic optimization perspective, informed drivers may also divert to alternate routes, either by their own choice or by recommendation by the vehicle's GPS unit. The distance of 10 kilometers is chosen so as to ensure that there is a reasonable number of disconnected clusters between source and destination, when vehicle density is low.

The following sections will present primarily simulation results. When available, data from the analytical model presented in Sec. III will be overlaid with the simulation data for the purpose of validating our approach.

B. Decelerating Vs. Queuing

We begin by evaluating the re-healing time in a network where tail vehicles decelerate, versus a similar network where vehicles just queue behind the source of the emergency message (e.g., an accident). We consider vehicle densities that go from ≈200 to ≈650 cars per hour, which represent low- and medium-density scenarios [1]. The vehicle's top speed is set to 30 m/s, and if deceleration occurs, vehicles do so at a deceleration level of 5 ms^{-2}.

Fig. 1 shows the total re-healing time required to propagate an emergency message to a destination that is 10 km away from the event that caused the message. For 1-way traffic with deceleration, the data from the analytical model ('An.') is also plotted, for comparison.

It can be seen that deceleration is only effective for scenarios with one-way traffic, where the re-healing time can improve between 30% to 60% (depending on traffic volume) versus the queueing scenario. The data also shows a very good agreement between the simulation data and the analytical model predictions for one-way traffic with deceleration.

This result seems to indicate that deceleration is very inefficient in scenarios with two-way traffic, where the forwarding of emergency messages through opposite-lane vehicles can be much faster. One can see minimal improvements in re-healing time when using both delivery methods (decelerating on the lane of interest plus forwarding with opposite-lane vehicles), but the impact of requiring tail vehicles to decelerate might not be justified for such a modest gain.

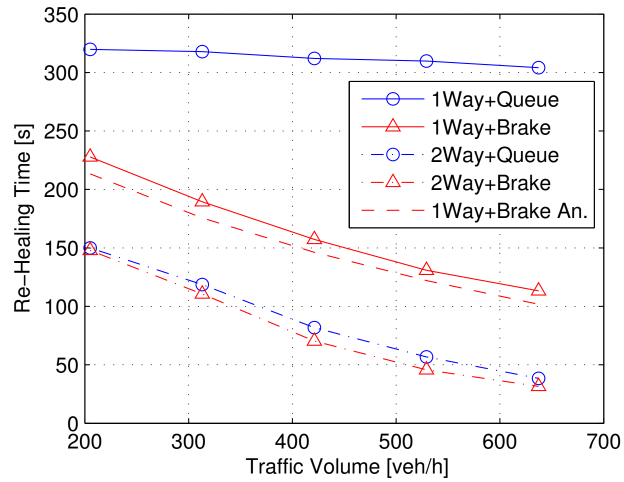

Figure 1. Re-healing time comparison between queuing behind accident and decelerating.

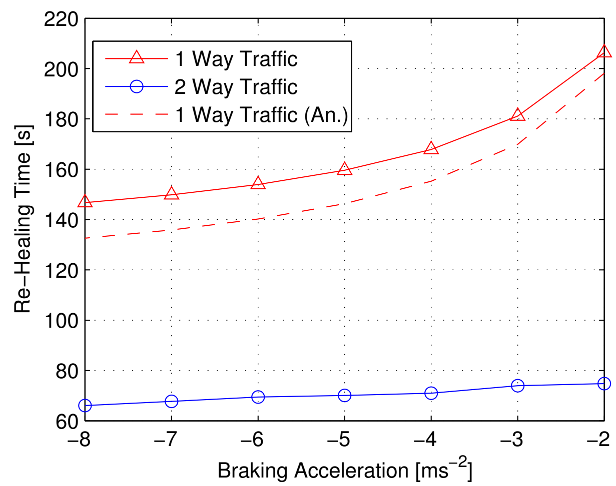

Figure 2. Re-healing time as a function of deceleration.

C. Deceleration

We now study the relation between deceleration and re-healing time. In a real-life scenario deceleration is unlikely to be a controllable variable, as each driver will brake the vehicle differently, but nevertheless deceleration can be estimated based on road conditions and driving patterns.

Fig. 2 shows what kind of gains can be had given an expected deceleration. For the 1-way traffic scenario, re-healing time can improve up to 28%, while for the 2-way traffic scenario, the effects of deceleration are negligible. Again, there is a good match between simulation results and data from the analytical model ('An.').

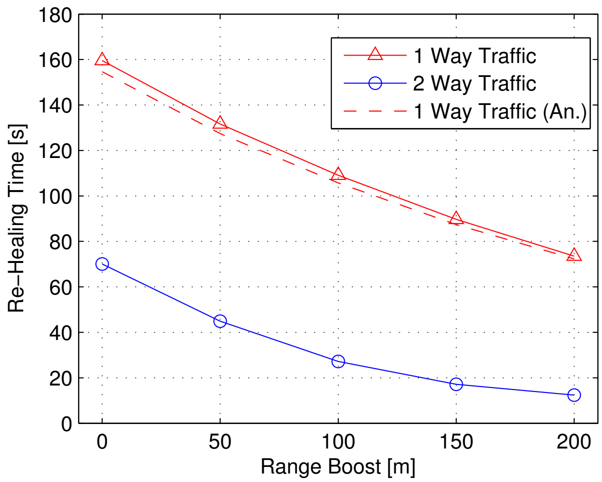

Figure 3. Effects of tail vehicle range boosting on the network's re-healing time.

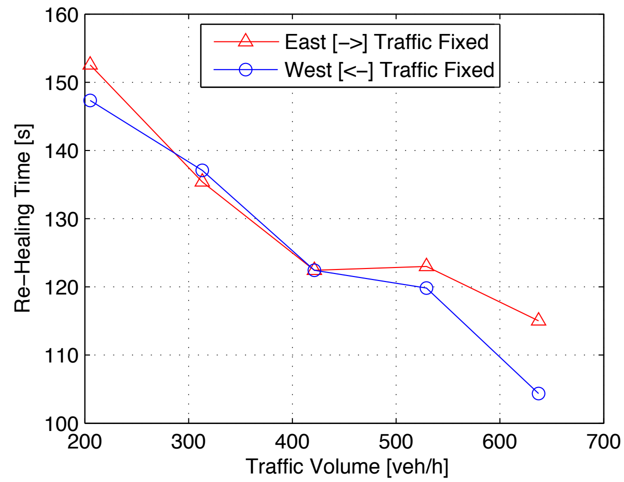

Figure 4. Re-healing time in a two-way scenario with different traffic density per lane.

D. Range Boosting

To evaluate the effects of an increase in transmission power by the last vehicle in the cluster, we ran sets of simulations where that vehicle's radio range is instantly increased as it receives an emergency message broadcast, while also decelerating at a 5 ms^{-2} level. We evaluate the 10 km re-healing time with radio ranges boosted between 50 m and 200 m, from a base range of 250 m. We have also ensured, through simulations with 802.11p radio models, that these range boosts are possible without exceeding the maximum transmission power of 48.8 dBm EIRP that is defined in the 802.11p standard.

In Fig. 3, we see that power control at the tail nodes can yield gains for both the one-way and two-way traffic scenarios. With only one lane of traffic, the delay can be reduced by as much as 53%, while for the two-way scenario, delay can go down by as much as 78%, from $70s$ to just $15s$ to reach a span of 10 km. Data from the analytical model ('An.') is a near-perfect match to the simulation results.

E. Varying density in single lane

An emergency message travels in a single direction in the lane of interest, and in a 2-way traffic scenario, it can be carried by opposite-lane vehicles. We study the effects of varying traffic density on a single lane, to determine if a lack of vehicles in the opposite lane can be more detrimental than a lack of vehicles in the lane of interest, or vice-versa.

The results of a set of simulations where traffic is fixed in one lane and varied in the other can be seen in Fig. 4, where the east-bound lane is where the message originates and the deceleration occurs, while the west-bound lane is the opposite lane. The data shows that traffic density is equally important both in the main lane (where deceleration occurs) and in the opposite lane where vehicles carry the emergency message across. For higher traffic densities, the density of cars on the main lane is more important than on the opposite lane, and an increase in it (i.e., fixing density on the west-bound lane) yields better results than an increase in opposite-lane traffic.

F. Deceleration & Power Control

The final set of results shows the combined effects of deceleration and power control in the re-healing time of the vehicular network. Figures 5 and 6 plot the re-healing time analysis for one-way and two-way traffic, respectively, for selected pairs of edge vehicle radio power boost and deceleration. The range boost levels of $\{0, 100, 200\}m$, and the deceleration levels of $\{3, 4, 5\}ms^{-2}$ are considered, for traffic densities between 200 and 650 cars per hour.

1) 1-Way Traffic: With only one-way traffic in the road, Fig. 5 shows that both deceleration and power control have an impact on the re-healing time – however, decelerating yields comparatively small improvements against a radio power boost.

2) 2-Way Traffic: When two-way traffic exists in the road, the data in Fig. 6 confirms that decelerating vehicles in the lane of interest brings negligible improvements to the network's re-healing time, which had been hypothesized earlier with the data in Fig. 1.

This confirms that opposite-lane forwarding of emergency messages is substantially more efficient than deceleration in the lane of interest. Furthermore, one can see that power control at tail vehicles is crucial for a quicker message broadcast, and boosting the radio range by 100 m and 200 m can cut the total re-healing time down by $50-75\%$.

V. Discussion

Providing connectivity in sparse vehicular ad hoc networks remains a major challenge in the design and operation of vehicular networks, especially in disseminating safety messages in a timely manner. While conventional wisdom suggests that

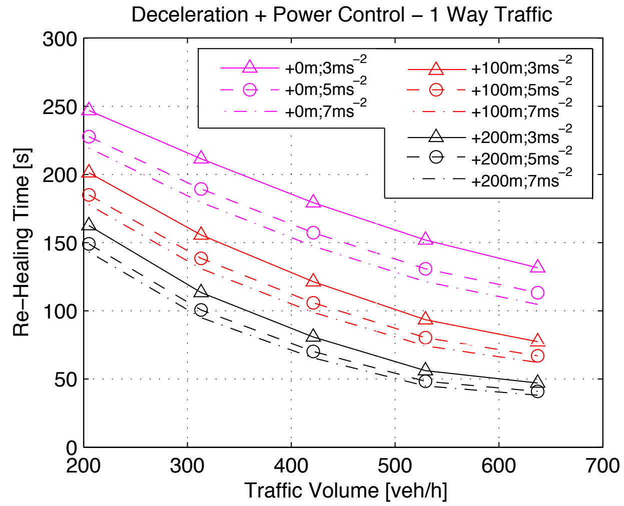

Figure 5. Re-healing time as a function of deceleration and tail vehicle power control, with one-way traffic only.

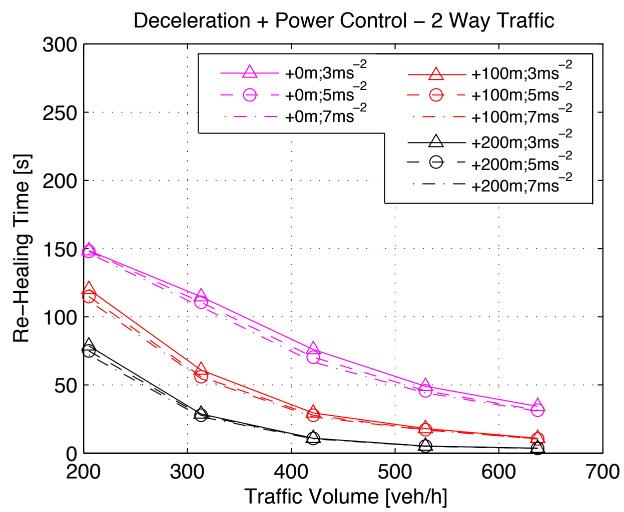

Figure 6. Re-healing time as a function of deceleration and tail vehicle power control, with two-way traffic.

road-side units might be able to mitigate this problem, the past decade has proven that this is a costly proposition that might be hard to implement on a large scale. These realities motivate our quest for finding alternative solutions that rely on the members of a vehicular ad hoc network as opposed to deploying additional hardware.

A. Social Impact

One issue that merits discussion is the social acceptability of the proposed techniques, in particular the one where vehicles reduce or halt their movement while on the highway. While there is no doubt that such a request is an inconvenience to the drivers, one should also note that: *i)* it is only asked of for the transmission of important safety messages, which can be likened to the way drivers now give way to emergency vehicles; *ii)* it only applies in low-density scenarios – network connectivity is not an issue with large numbers of vehicles; and *iii)* only tail vehicles are asked to decelerate, further reducing the number of affected drivers.

B. Approach

In this work, we have also opted to evaluate a more straightforward method for power control. In dense networks, power control schemes must try to not be disruptive, by progressively increasing transmitted power in a staircase fashion, while monitoring the power levels of surrounding nodes. In sparse networks, however, the lack of nodes is the main concern, and cluster tail nodes are by definition disconnected from the rear nodes. We therefore believe that a more aggressive boosting of power levels might be more appropriate. In particular, in sparse networks for safety message broadcasting, it is our opinion that the urgency of the messages surpasses the concerns of mitigating interference. Safety messages are, by design, small, and infrequent broadcasting of small packets at high power levels should not be detrimental to the overall performance of the network.

In this paper we showed that the deceleration of vehicles and the boosting of transmission power can make vehicles serve as roadside units in a dynamic manner. Overall, our results show that the approaches that we pursued for alleviating the issue of safety message delay in sparse networks are very promising.

VI. Conclusion

In this paper, we evaluated the impact of two different parameters in the broadcast time of safety messages, on infrastructure-less highways, during low-traffic periods (or during the initial deployment phase of the DSRC technology) where the network becomes sparse and disconnected. We developed mathematical models and a simulation platform to analyze the communication improvements when employing tail vehicle deceleration, and tail vehicle power control. The metric of choice was the re-healing time, which is the time it takes for a safety message to be broadcast across a given span of road.

It has been shown that reducing the speed of certain vehicles (i.e., deceleration) in order to quickly close gaps in sparse networks can yield good improvements, but only if the road in question has one-way traffic exclusively. With two-way traffic roads, our study shows that deceleration is not as effective, as message forwarding by opposite-lane vehicles is substantially more efficient. This is true even when the density of opposite-lane vehicles is low. Conversely, the application of power control and radio range boosting techniques to cluster edge vehicles can lead to significant gains in the re-healing time of safety messages, both in the cases of one-way and two-way traffic.

In light of these results, a suitable approach would be to enforce both deceleration and power control in sparse one-way highway vehicular networks, and restricting networks of two-way traffic to power control alone. For future work, our goal is to apply these techniques to vehicles capable of assessing the road conditions, vehicle density and the presence of two-way traffic, and propose a protocol for dynamic and self-organized mobile gateway announcement and selection.

REFERENCES

[1] N. Wisitpongphan, Fan Bai, P. Mudalige, V. Sadekar, and O.K. Tonguz, “Routing in Sparse Vehicular Ad Hoc Wireless Networks,” IEEE Journal on Selected Areas in Communications, vol. 25, no. 8, pp. 1538-1556, 2007.

[2] A.B. Reis, S. Sargento, and O.K. Tonguz, “On the Performance of Sparse Vehicular Networks with Road Side Units,” 2011 IEEE 73rd Vehicular Technology Conference (VTC Spring), pp. 1-5, May 2011.

[3] A.B. Reis, S. Sargento, F. Neves, and O.K. Tonguz, “Deploying Roadside Units in Sparse Vehicular Networks: What Really Works and What Does Not,” IEEE Transactions on Vehicular Technology, vol. 63, 2014.

[4] O.K. Tonguz, “Biologically inspired solutions to fundamental transportation problems,” IEEE Communications Magazine, vol. 49, no. 11, pp. 106-115, 2011.

[5] W. Viriyasitavat and O.K. Tonguz, “Cars as Roadside Units: A Cooperative Solution,” 2012 IEEE Vehicular Technology Conference (VTC Fall), pp. 1-5, Sep. 2011.

[6] O.K. Tonguz and W. Viriyasitavat, “Cars as roadside units: a self-organizing network solution,” IEEE Communications Magazine, vol. 51, no. 12, pp. 112-120, Dec. 2013.

[7] Bojin Liu, B. Khorashadi, D. Ghosal, Chen-Nee Chuah, and M.H. Zhang, “Assessing the VANET’s Local Information Storage Capability under Different Traffic Mobility,” 2010 Proceedings IEEE INFOCOM, pp. 1-5, March 2010.

[8] Agarwal, A.; Starobinski, D.; Little, T. D C, “Analytical Model for Message Propagation in Delay Tolerant Vehicular Ad Hoc Networks,” IEEE Vehicular Technology Conference (VTC Spring), pp. 3067-3071, May 2008.

[9] G. Resta, P. Santi, and J. Simon, “Analysis of multi-hop emergency message propagation in vehicular ad hoc networks,” Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc ’07), pp. 140-149, 2007.

[10] W. Viriyasitavat, Fan Bai, and O.K. Tonguz, “UV-CAST: An urban vehicular broadcast protocol,” IEEE Vehicular Networking Conference (VNC), pp. 25-32, Dec. 2010.

[11] O.K. Tonguz, W. Wisitpongphan, and Fan Bai, “DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks,” IEEE Wireless Communications, vol. 17, no. 2, pp. 47-57, Apr. 2010.

[12] E. Fasolo, A. Zanella, and M. Zorzi, “An Effective Broadcast Scheme for Alert Message Propagation in Vehicular Ad hoc Networks,” IEEE International Conference on Communications (IEEE ICC), vol. 9, pp. 3960-3965, Jun. 2006.

[13] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein, “Vehicle-to-Vehicle Communication: Fair Transmit Power Control for Safety-Critical Information,” IEEE Transactions on Vehicular Technology, vol. 58, no. 7, pp. 3684-3703, Sep. 2009.

[14] Jun Peng and Liang Cheng, “A Distributed MAC Scheme for Emergency Message Dissemination in Vehicular Ad Hoc Networks,” IEEE Transactions on Vehicular Technology, vol. 56, no. 6, pp. 3300-3308, Nov. 2007.

[15] Yuanguo Bi, L.X. Cai, Xuemin Shen, and Hai Zhao, “Efficient and Reliable Broadcast in Intervehicle Communication Networks: A Cross-Layer Approach,” IEEE Transactions on Vehicular Technology, vol. 59, no. 5, pp. 2404-2417, Jun. 2010.

[16] H. Alshaer and E. Horlait, “An optimized adaptive broadcast scheme for inter-vehicle communication,” VTC 2005-Spring: 2005 IEEE 61st Vehicular Technology Conference, vol. 5, pp. 2840-2844, Jun. 2005.

[17] J. Sahoo, E. Wu, P.K. Sahu, and M. Gerla, “BPAB: Binary Partition Assisted Emergency Broadcast Protocol For Vehicular Ad Hoc Networks,” ICCCN 2009: Proceedings of 18th International Conference on Computer Communications and Networks, pp. 1-6, Aug. 2009.

[18] M. Fiore, C. E. Casetti, C. Chiasserini, and P. Papadimitratos, “Discovery and Verification of Neighbor Positions in Mobile Ad Hoc Networks,” IEEE Transactions on Mobile Computing, vol. 12, no. 2, pp. 289-303, Feb. 2013.

[19] Information Sciences Institute, University of Southern California, “The Network Simulator - ns-3,” Dec. 23, 2011. [Online]. Available: http://www.nsnam.org/