On the Performance of Sparse Vehicular Networks with Road Side Units

A. B. Reis*†, S. Sargento†, and O. K. Tonguz*

*Dept. of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213-3890, USA
†Instituto de Telecomunicações, Universidade de Aveiro, 3810-193 Aveiro, Portugal

***Abstract*—The reliability of communication in vehicular networks depends mostly on the density of DSRC-enabled vehicles that form the network. In highway scenarios, and depending on the time of day, the probability of having a disconnected vehicular network can be very high, which hinders communication reliability. To improve communication in these scenarios, infrastructure points known as Road Side Units (RSU) may be used. RSUs, however, have an associated cost, and therefore the number of RSUs needs to be minimized while still providing a significant improvement on communications.**

In this paper we study the effect of including RSUs as relay nodes to improve communication in highway scenarios. We model the average time taken to propagate a packet to disconnected nodes (denoted as re-healing time) when considering both scenarios of connected and disconnected RSUs. We then compare the results of both these models and of a model with no RSUs. Results show significant improvements with RSU deployments, both connected and disconnected, particularly in multi-cluster communication scenarios.

***Index Terms*—VANET, Vehicular Ad-Hoc Networks, Road-Side Units, Sparse Networks, Traffic Modeling, Re-Healing Time.**

I. INTRODUCTION

The dynamics associated with mobile nodes make vehicular networks susceptible to partitioning. Moreover, vehicle density, limited radio range and even small penetration rates of vehicles equipped with Dedicated Short-Range Communications (DSRC) devices may contribute to the disconnection between nodes in a vehicular network, leading to the so-called sparse network phenomenon. Research reported in [1] shows that even during rush hours, where vehicles are expected to be very close to each other, a market penetration rate of DSRC-enabled vehicles of less than 35% can lead to the same kind of disconnected network problem.

In sparse networks, the communication between vehicles can be characterized by very high transmission delays which make the communication extremely slow. Moreover, these delays may sharply increase the buffer requirements for streaming media, and lead to failure of network protocols that do not expect large round-trip times. In [1], a model for deriving the packet delivery delay between disconnected vehicles, the re-healing time, was proposed. It was shown that this time can increase to values in excess of 100 seconds in multi-hop disconnected communications, which is unacceptable for vehicular networks.

Road Side Units (RSUs) can be used to overcome this problem. These infrastructure points are fixed base stations deployed along the road with the goal of increasing the overall coverage of the vehicular network. Equipped with better hardware and less power and cost constraints than the units used in the vehicles, they are expected to enhance the network's performance and improve the propagation distance of messages. A network of RSUs can also serve as a backbone, enabling access to other WANs or to the Internet. Although the presence of these units may significantly improve communication performance, the cost of deploying and supporting RSUs in vehicular environments can be very high. The trade-off between the required number of RSUs and the vehicular network performance in sparse scenarios is thus an important problem that needs careful study.

The aim of this paper is to give insight into this tradeoff: to assess the improvement on vehicular network performance for a specific number of RSUs. To this end, we develop mathematical models (based on [1]) to determine the average delay of a packet between disconnected source and destination in the presence of RSUs as relays. We study both the scenarios of disconnected RSUs, where units are deployed without a physical connection between them, and connected RSUs, where units are connected through fiber or broadband wireless links. The models cover both the one-gap (the disconnection between adjacent clusters) and multi-gap communication scenarios. The results obtained for a specific number of RSUs (connected and disconnected) are compared with the ones where no RSUs are in place. The results show that significant improvements can be achieved with RSUs. For single-gap communications, the transmission delay can be reduced by 15% to 30%; for traversing multiple gaps, up to 25% reduction in end-to-end delay with disconnected RSUs is achievable, and with connected RSUs the decrease in delay can be of several orders of magnitude, depending on the desired area of interest.

The remainder of this paper is organized as follows. An overview of the state of the art in infrastructure-supported vehicular networks is presented in Section II. Section III describes the analytical models developed to model delays in disconnected and connected RSU deployments. The analytical results are depicted in Section IV together with a discussion on the expectations with both types of RSU configurations in vehicular networks. Finally, concluding remarks and future research directions are presented in Section V.

II. Related Work

The interest in vehicular networks research has been increasing exponentially over the last few years. A pure vehicle-to-vehicle (V2V) network, albeit possible, may not be sufficient to ensure good performance when the network is sparse. Therefore, the topic of vehicle-to-infrastructure (V2I) communication, where RSUs with better equipment are deployed to increase network quality, is of paramount importance.

The physical distribution of RSUs to optimize communication is an important design consideration for any real-life scenario, and research on this topic is relatively scarce. [2] presents strategies for deploying RSUs at junctions by using a measure of centrality, but suggests placing RSUs at popular junctions (where traffic density would not lead to disconnection), and reports end-to-end delays of several minutes. In [3], placement of gateways for Internet access is considered, but under the assumption of having full coverage by RSUs. Research in [4] analyzes the connectivity probabilities in infrastructure-based vehicular networks, however no measures of delay are given, and opposite-lane message relaying is not considered. Finally, in [5], a framework based on queuing theory gives a delay bound for relaying messages to an RSU through V2V communication, but traffic densities are not representative of sparse networks and no effort is made to reach delays under 100 seconds.

None of these studies give a clear comparison between using connected and disconnected RSUs in quantitative terms. The work reported in this paper aims to make that comparison, by developing analytical models that assess the improvements brought to vehicular communications by both types of RSU deployments.

III. Analytical Models

This section presents the analytical models developed for disconnected and connected RSU deployment scenarios. One can envision several specific scenarios where RSUs can provide significant benefits in communication:

- RSUs as communication relays;
- RSUs as broadcasters of information (one-time or repeated information);
- RSUs as infrastructure communication points to and from a WAN (e.g., Internet).

When one considers the benefit of having RSUs assist communications in sparsely connected networks, the most critical scenario is the first one, where we envision deployments of RSUs to enable relaying of information when there is severe disconnection between vehicles. Therefore, this paper addresses specifically this scenario, where we consider that vehicles flow in both directions and that RSUs, if present, are aiding the relay of information between disconnected sources and destinations.

In order to evaluate the performance improvements due to a deployment of RSUs, we first seek a mathematical model to characterize traffic patterns on a highway. In [1], a comprehensive traffic model based on empirical data collected from a dual-loop detector along the Interstate 80 freeway was reported. This study shows how the spacing between vehicles in sparse networks follows an exponential distribution, allowing for many characteristics of such networks to be derived. One of them in particular, the re-healing time, is a crucial metric for the research at hand, and is defined as the time necessary to deliver a message across two adjacent clusters. The main goal of an RSU deployment is to reduce this communication gap, i.e., reduce the re-healing time.

In this paper we adopt the same notation as the one used in [1]: $\mathbf{C_N}, \mathbf{C_L}$: cluster size (number of vehicles) and cluster length (meter); $\mathbf{R}$: vehicle radio range; $\mathbf{v_e}, \mathbf{v_w}$: same-lane and opposite-lane vehicle speed; $\lambda_\mathbf{e}, \lambda_\mathbf{w}$: vehicle densities per meter; $\mathbf{E}[\mathbf{S_{inter}}]$: same-lane inter-cluster spacing; $\mathbf{E}[\mathbf{S'_{inter}}]$: opposite-lane inter-cluster spacing; $\mathbf{E}[\mathbf{S_{intra}}]$: intra-cluster vehicle spacing; and P_d: probability of being the last vehicle in a cluster. We also consider that the transmission delay between connected units (spatial delay) is negligible.

A. Re-healing with assistance from disconnected RSUs

The first model evaluates how a deployment of fixed RSUs along a highway can improve a sparse vehicular network. Working with the analytical framework described in the previous section, we determine which communication scenarios can benefit from the presence of an RSU.

1) Improvements in a best-case scenario: In a best-case scenario, depicted in Fig. 1a, where the source vehicle is directly connected to a vehicle on the opposite lane to carry its message, improvements can be achieved when an RSU is positioned in a way where it can forward the message from the opposite-lane vehicle to the destination, effectively acting as if it were a vehicle (Fig. 1c). In a multi-gap scenario, an improvement is only seen if the destination vehicle's cluster has a new opposite-lane vehicle in range; if not, the old opposite-lane vehicle will be the next message carrier, and no gain is seen. On average, the reduction in the travel distance of the opposite-lane vehicle is:

$$E[L_I] = p_{fav} \cdot R_I = \frac{2{R_I}^2}{C_I} \cdot \left(1 - e^{-\lambda_w \cdot E[C_L]}\right) \tag{1}$$

where p_{fav} is the probability for an RSU to be positioned favorably for this assistance, $E[C_L]$ is the average cluster length, and R_I and C_I are the RSU's radio range and the spacing between RSUs, respectively. The modified re-healing time for a best-case scenario with disconnected RSUs, $E[T_{r_1}]$, is given by:

$$\begin{aligned} E[T_{r_1}] = \Bigg\{ & (1-P_d) \cdot \frac{1}{v_e+v_w} \cdot \left\{ \frac{1}{\lambda_e} - \frac{1}{2} E[S_{intra}] \cdot \right. \\ & \left. \cdot E[C_N | C_N \leq k] - E[L_I] \right\} + P_d \cdot \frac{1}{v_e+v_w} \cdot \\ & \cdot \{R + E[S_{inter}] - R - E[L_I]\} \Bigg\} \cdot p_{10}, \end{aligned} \tag{2}$$

where the first term is the re-healing time when the source is part of a cluster, and the second term refers to isolated vehicles (as in [1]); p_{10} is the probability that the opposite-lane vehicle is disconnected from the destination (and the complementary event has zero re-healing time).

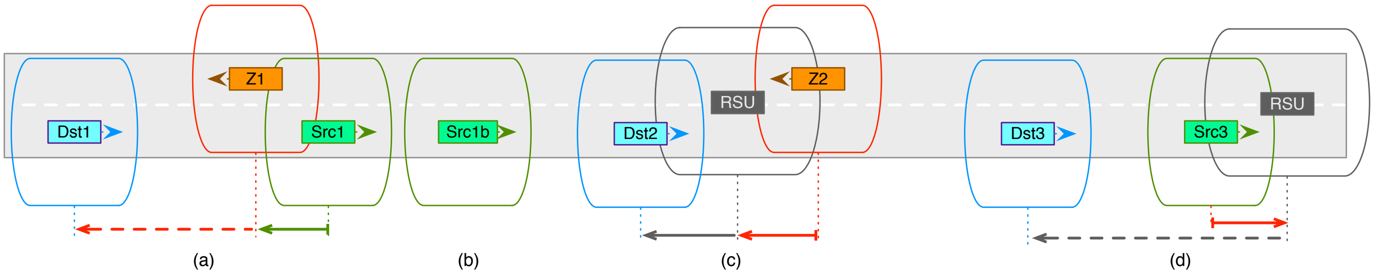

Figure 1. Illustrations for: (a) best-case scenario; (b) worst-case scenario; (c) RSU as a last-hop relay; (d) RSU as a 'store and forward' relay. Solid arrows represent spatial delay, dashed arrows represent temporal delay.

2) Improvements in a worst-case scenario: In a worst-case scenario (Fig. 1b), the source vehicle is not connected to any vehicle capable of forwarding its message, and must wait for one to come into range (e.g. vehicle $Z2$ in Fig. 1c).

With the presence of RSUs, a new scenario where an RSU acts as a message carrier becomes possible (Fig. 1d). This occurs when the delay to forward a message through an opposite-lane vehicle is larger than the delay for the source to get a message to an RSU, plus the destination reaching that RSU. This event occurs with probability p_{2A}:

$$p_{2A} = P\left[S'_{inter} > K\right] = e^{\lambda w(R-K)}, \tag{3}$$

where $K = 2[(E[S_{inter}]-R_I+C_I/2)(v_e+v_w)-(E[S_{inter}]-R)]/v_e$. The re-healing time for this new scenario is:

$$E[T_{r_{2A}}] = \frac{1}{v_e} \cdot \left(\frac{C_I - 2R_I}{2} + E[S_{inter}]\right), \tag{4}$$

when considering an RSU as the sole message carrier.

If the previous scenario does not occur, then we are in the worst-case scenario, where the source vehicle is disconnected from both the destination and opposite-lane vehicles. In this case, the RSU can reduce the temporal delay from the opposite-lane vehicle to the destination as in Sec. III-A1 (and Fig. 1c). The worst-case scenario is defined by the delay from source to opposite-lane vehicle, $E[T_{r_{20}}]$, plus the delay from the opposite-lane vehicle to the destination, $E[T_{r_{21}}]$. One can rewrite the latter accounting for an RSU temporal delay reduction:

$$E[T_{r21}] = \frac{R + E[S_{inter}] - R - E[L_I]}{v_e + v_w} \tag{5}$$

The term $E[T_{r_{20}}]$ remains unchanged, and is the same as in [1].

The global re-healing time for the worst-case scenario, $E[T_{r_2}]$, is the combination of the first and second re-healing scenarios with probabilities p_{2A} and $1 - p_{2A}$, respectively.

B. Re-healing with assistance from interconnected RSUs

The second model characterizes re-healing time when the vehicles travel on a road covered by interconnected RSUs (Fig. 2). For this, we approximate the re-healing time as the delay for the source to reach an RSU, and the delay for the destination to also reach an RSU – these events occur in parallel and, on average, carry the same delay. Later, we show how this approach can be combined with the previous model to ensure the lowest re-healing time possible.

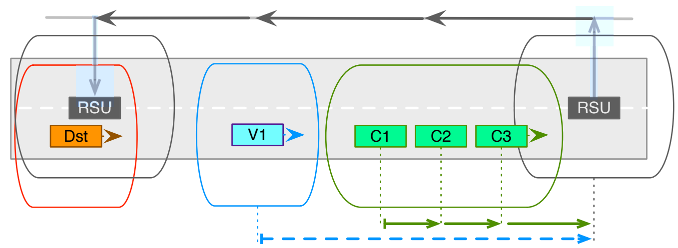

Figure 2. Illustration of a disconnected isolated vehicle (*V1*) and of a connected 3-vehicle cluster (*C1*, *C2*, *C3*) in a scenario of connected RSUs.

We begin by deriving equations for the average time a vehicle takes to reach its nearest RSU. We consider two separate scenarios: the vehicle can be isolated, or be part of a cluster, which will aid message transmission.

1) Isolated vehicle: It can be shown that the delay involved in an isolated vehicle reaching an RSU is given by:

$$\begin{aligned} E[T_{r_V}] &= E[T_{r_V}|V_d] \cdot Pr[V_d] + E[T_{r_V}|\neg V_d] \cdot Pr[\neg V_d] \\ &= \frac{C_I - 2R_I}{2 \cdot v} \cdot \left(1 - \frac{2R_I}{C_I}\right) \end{aligned} \tag{6}$$

where V_d is the event "Vehicle is disconnected from an RSU," and $E[T_{r_V}|V_d]$ is the re-healing time for such vehicles. For vehicles in the range of an RSU, the re-healing time $E[T_{r_V}|\neg V_d]$ is intuitively zero.

The isolated vehicle scenario occurs with probability $Pr[C_N = 1] = Pd(1 - Pd)^{C_N - 1} = e^{-\lambda_s \cdot R}$.

2) Vehicle in a cluster: The average travel distance is now reduced, on average, by half of the cluster's length, as cars in the cluster help forward the message. Also, all clusters whose length exceeds the distance between two RSU's consecutive radio ranges ($C_I - 2R_I$) can now be considered as permanently connected (i.e., zero re-healing). The average re-healing time for disconnected clusters is given by:

$$\begin{aligned} E[T_{r_C}] =& E[T_{r_C}|C_d \cap C_L < C_I - 2R_I] \cdot \\ & \cdot Pr[C_d] \cdot Pr[C_L < C_I - 2R_I], \end{aligned} \tag{7}$$

where C_d is the event "Cluster is disconnected from an RSU," C_L is the cluster length in meters, and $E[T_{r_C}|C_d \cap C_L < C_I - 2R_I]$ is the travel delay for disconnected clusters smaller than

$C_I - 2R_I$, given by:

$$E[Tr_C|C_d \cap C_L < C_I - 2R_I] = \frac{(C_I - 2R_I) - E[C_L|C_L < C_I - 2RI]}{2 \cdot v}, \quad (8)$$

with $E[C_L|C_L < C_I - 2RI]$ as the expected length of such clusters. The probability of cluster disconnection is $Pr[C_d] = 1 - (2R_I + C_L)/C_I$, and we also require the probability that a cluster is smaller than two RSU's consecutive radio ranges, $Pr[C_L < C_I - 2R_I]$.

The scenario where a vehicle is part of a cluster occurs with probability $Pr[C_N > 1] = 1 - Pr[C_N = 1] = 1 - e^{-\lambda_s \cdot R}$.

Two factors in the above equations, $E[C_L|C_L < C_I - 2RI]$ and $Pr[C_L < C_I - 2R_I]$, require knowing the distribution of the vehicle clusters' lengths. This distribution is not trivial to compute algebraically, and therefore we have determined the following PDF for cluster length, based on empirical evidence from vehicular network simulations of the traffic model[1]:

$$f_{C_L}(c_L) = \quad (9)$$

$$\begin{cases} k(R,\lambda) \cdot \left(R \cdot k(R,\lambda) + e^{-R/\mu(R,\lambda)}\right)^{-1} & 0 < c_L < R \\ \frac{\mu(R,\lambda)^{-1} \cdot e^{-c_L/\mu(R,\lambda)}}{R \cdot k(R,\lambda) + e^{-R/\mu(R,\lambda)}} & c_L \geq R \end{cases}$$

where $k(R,\lambda) = \alpha + \beta \cdot \lambda + \frac{\gamma}{R + \delta}$, and $\mu(R,\lambda) = \kappa + \omega \cdot e^{\theta \cdot R \cdot \lambda}$.

The required probability and conditional expectation are both straightforward to compute from $f_{C_L}(c_L)$.

IV. Re-healing Time Analysis with Multiple Road Side Unit Models

In this section we present the results of our analytical models, and show how RSUs can improve re-healing time in sparse vehicular networks. Our two main performance metrics are:

- **Single-gap re-healing time**, the delay associated with forwarding a message from a source to a destination in the next cluster on the same lane; and,
- **Multi-gap accumulated delay**, the time required to transfer a message between a source and a destination separated by a span of multiple disconnected clusters.

A. Single-gap re-healing time

For the single-gap scenario, we analyze re-healing time as a function of the density of vehicles in the road. The densities in both lanes are considered to be similar. We consider a road where RSUs are deployed with intervals of 1000 and 750 meters, and, conservatively, have the same radio range as vehicles. Vehicle speeds were set to $30\,[m/s]$ (both lanes), and radio ranges to $250\,[m]$. Fig. 3 shows a comparison of all three scenarios, for densities that go from $\approx$200 to $\approx$700 cars per hour.

It can be seen that a deployment of isolated RSUs can yield a reduction of 1 to 5 seconds in the network's mean re-healing time. This advantage becomes smaller for denser networks, as disconnection becomes less of an issue.

[1]Interpolation constants extracted from simulations: $\alpha = 0.0003295$, $\beta = -0.2942$, $\gamma = 0.7212$, $\delta = -24.67$, $\kappa = -161.1$, $\omega = 199.8$, $\theta = 0.9063$.

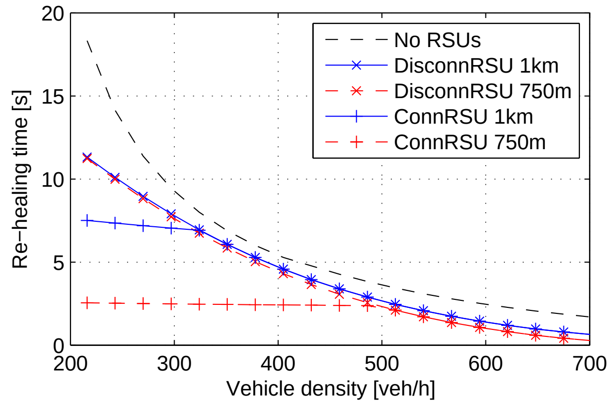

Figure 3. Single-gap re-healing time.

A deployment of connected RSUs shows substantial improvement for very sparse networks, for densities under $\lambda \approx 325\,[veh/h]$ for $C_I = 1000m$, and $\lambda \approx 475\,[veh/h]$ for $C_I = 750m$. Due to the way the scenario for connected RSUs was designed, note that, for a transmission over a single hop and given sufficient vehicle density in both lanes, opposite lane vehicles may be able to deliver a message in shorter time than if going through connected RSUs. This is evident from Fig. 3.

For a single-hop transmission, we observe that the best re-healing time in a road with connected RSUs is the shortest time between the opposite-lane store-carry-forward approach, and the delivery-through-infrastructure approach. This is particularly valid for safety messages, where an ideal vehicular network must try to broadcast the message through any means possible, and the re-healing metric is the shortest time for that message to be delivered.

B. Multi-gap accumulated delay

In a multi-gap scenario, we study the delay involved in propagating a message over a large length of road, up to 30 km, which is essentially an accumulation of re-healing times dependent on the number of clusters on the road and the inter-cluster spacing between them.

In the no-RSU and disconnected RSU models, store-carry-forward is the primary mechanism of transmission. For these scenarios, we fix the vehicle density in both directions and determine the mean number of clusters to be traversed. Then, the total delay is the sum of all re-healing times required to get a message from each cluster to the next. For the model where RSUs are connected through a backbone, we determine the number of RSUs the message must travel to reach the destination, and add a conservative 50 ms delay per hop to the re-healing time.

Fig. 4 is the key result of this paper, and it plots accumulated re-healing times for all three scenarios as a function of the length of road to transmit a message across, in a network where λ is fixed to a value indicative of a sparse network ($\lambda = 425\,[veh/h]$). All other parameters are the same as in the single-gap scenario given above. This is a scenario where a deployment of RSUs is capable of yielding significant gains.

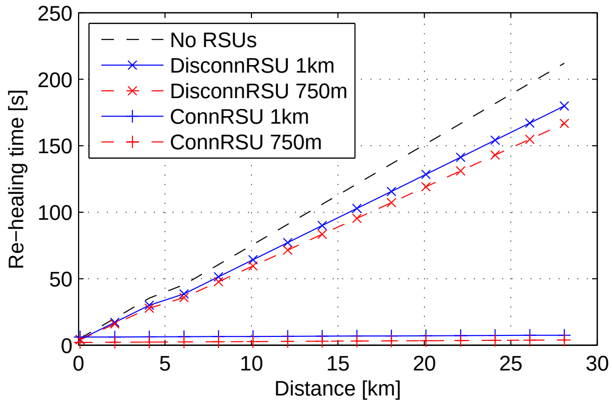

Figure 4. Total end-to-end delay to transmit over large distances.

Table I
MAXIMUM RSU DISTANCE TO MEET RE-HEALING THRESHOLDS

	Threshold	**DisconnRSU**	**ConnRSUs**
Per-gap delay	2s	295m	740m
	4s	770m	880m
End-to-end delay	2s	*not possible*	720m
	4s	*not possible*	860m

The mere presence of disconnected RSUs steadily reduces the multi-gap accumulated delay by $\approx$ 20%, with even higher gains possible with closer-spaced RSUs. Connected RSUs, as intuitively expected, can be seen as the only way to carry messages across long lengths of road in under 5 seconds.

C. Threshold-dependent RSU density

Our last set of results evaluates how hypothetical protocol requirements constrain the minimum number of RSUs to be deployed, or, from a different point of view, how an infrastructure-assisted vehicular network can be designed in order to support protocols with specific delay requirements.

Table I shows the maximum distance allowed between RSUs to meet thresholds of 2 and 4 seconds, for a traffic density of $\lambda = 425\ [veh/h]$, and for a distance of 30km for the end-to-end scenario. These values are indicative for the following cases: a protocol that needs to keep delay in check on a per-gap basis, but is not concerned with the accumulated delay (e.g. an ad-hoc routing protocol such as AODV [6]); and a protocol that needs to ensure a total end-to-end delay below a given threshold (e.g. reliable transport).

On a per-gap basis, table I shows that for a 2 second threshold a deployment of connected RSUs requires the least number of RSUs, less than half the number of RSUs a disconnected deployment would require. For a 4 second threshold, a deployment of connected RSUs would require approximately 12% less units than its disconnected counterpart.

When traversing large distances, disconnected RSU deployments are unable to match the thresholds, unless they are placed so close together that they effectively become connected.

D. Discussion

The overall results show that RSUs are indeed able to significantly decrease the re-healing time in vehicular communications. However, for scenarios with low vehicle density, a significant decrease can only be achieved with a strong deployment of RSUs, but the underlying costs of such a large deployment scenario may be prohibitive. For example, spacing RSUs 770 meters apart in a 30 Km road section would require a deployment of 39 units.

In scenarios with multiple clusters, the connection between RSUs can greatly reduce the time to transmit information between vehicles. Again, this connection requires a large investment on broadband communications along the roads. Thus, the support of RSUs to solve the disconnected network problem is still an important issue to tackle, to be able to provide reliable communications for vehicular applications.

V. CONCLUSION

In this paper, we developed mathematical models to analyze the communication improvements in sparse vehicular networks when employing RSUs to work as relays. The models determine the *re-healing* time, which is the time required to transmit information between source and destination in a two-way road scenario in the presence of RSUs, both disconnected and connected units. The results show that this time is significantly reduced in the presence of RSUs, where a larger improvement is achieved for the case of connected RSUs. However, the most significant improvements are seen in scenarios with a high density of deployed RSUs on the roads. Moreover, interconnected RSUs, which present great advantages when the information travels multiple clusters, require the support of broadband wired or wireless communications to be available along the roads or highways. Therefore, further research is required to ensure reliable vehicular communications with a moderate investment on highways.

As part of our future work, the immediate goal is to assess all the benefits of RSUs in different communication scenarios, such as when they are used as periodic broadcasters of information. We also plan to investigate new approaches to RSU deployment that can yield the same benefits without such costly investments.

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