Cars as Roadside Units: A Self-Organizing Network Solution

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ABSTRACT

Deploying roadside units, RSUs, for increasing the connectivity of vehicular ad hoc networks is deemed necessary for coping with the partial penetration of DSRC radios into the market in the initial stages of DSRC deployment. Several factors, including cost, complexity, existing systems, and lack of cooperation between government and private sectors, have impeded the deployment of RSUs. In this article, we propose to solve this formidable problem by using a biologically inspired self-organizing network approach whereby certain vehicles serve as RSUs. The proposed solution is based on designing local rules and the corresponding algorithms that implement them. Results show that the proposed approach can increase the message reachability and connectivity substantially.

INTRODUCTION

Successful deployment of vehicular ad hoc networks (VANETs) where information (e.g., traffic, road information, and safety messages) is sent, forwarded, and received by vehicles depends on the adoption of a new wireless technology, dedicated short-range communications (DSRC). Since it is anticipated that DSRC technology might be a mandate for modern vehicles effective 2017, with high probability, vehicle-to-infrastructure (V2I) communications-based networks will be the first type of vehicular ad hoc networks (VANETs)[1] that might be implemented and, as such, could accelerate the adoption of DSRC.

Besides V2I applications (e.g., Internet access), additional infrastructure can also be used to improve connectivity of vehicle-to-vehicle (V2V) networks. In addition to growing demand for V2X traffic[2] and the fact that V2V applications are confined to a particular geographical area, installing special roadside units (RSUs) has emerged as an attractive solution (especially to the U.S. Department of Transportation) for providing infrastructure support as RSUs limit information to being disseminated within a confined area, thus resulting in smaller message delay, better information security, and possibly lower communications cost.

While RSUs seem to be a very promising solution for improving V2V communications, the cost of manufacturing, installing, and maintaining these units seem to be prohibitive for the large-scale deployment of RSUs. For example, a simplistic form of RSU (e.g., roadway probe beacons) requires $13,000–$15,000 per unit capital cost and up to $2400 per unit per year[3] for operation and maintenance [1]. In addition to cost, the effectiveness and utilization rate of RSUs may also depend on the number of DSRC-equipped vehicles that are present in a given area. As an example, consider an accident notification message; RSUs will be utilized only for vehicles within a small region that is relevant to the notification message, typically a 4 mi^2 area around the accident scene.

In this article, based on a new biologically inspired networking paradigm, we propose to leverage the initially available DSRC-equipped vehicles to be used as *temporary RSUs*. Vehicles that act as temporary RSUs can make brief stops during which they act as a communication bridge for other vehicles in the network [2, 3]. We envision that using vehicles as RSUs could improve not only message reachability and network connectivity, but also accelerate the adoption of DSRC in addition to avoiding the cost of deploying RSUs.

PROBLEM STATEMENT

The U.S. Department of Transportation (DoT) was expected to have nationwide deployment of the roadside infrastructure in 2008 [4]. This plan, however, did not materialize, and to date very few RSUs have been deployed. The major reasons that prevented the success of the plan are summarized below.

JUSTIFYING THE BENEFITS THAT RSUS PROVIDE IS DIFFICULT

Determining the value of such a radical proposition in uncertain future markets has proven to be nontrivial and fairly complicated. Even though the benefits of V2V and V2I systems in terms of safety, traffic efficiency, and environment are clear and have been reported in [5], the full benefits of DSRC technology cannot be realized unless the technology is widely adopted by the market. Such economic justification

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[1] VANETs can be based on vehicle-to-infrastructure (V2I) and/or vehicle-to-vehicle (V2V) communications.

[2] V2X is an abbreviation used for both V2I and V2V communications.

[3] The price quote includes the cost of both roadside equipment and roadside wireless communications.

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becomes more difficult when there are other traffic information infrastructures such as dynamic message sign (DMS) and the 5-1-1 system already in place [6]. These existing systems provide both safety and traffic efficiency benefits (i.e., roadside assistance helps alert drivers of slow vehicles ahead and/or upcoming work zones, while a transportation and traffic information telephone hotline allows travelers to choose the most efficient mode and route to their final destination). Proven effectiveness, high user satisfaction [6], existing widespread deployment, and already invested capital[4] into the existing systems have further impeded the nationwide deployment of RSUs.

Global Cooperation and Partnership with the Private Sector

The deployment of roadside infrastructure (i.e., through the DoT's VII program) requires major collaboration and coalition of public and private sectors (e.g., U.S. DoT, state and city authorities, auto companies, and other for-profit and non-profit organizations). However, the willingness of the public and private sectors to cooperate in this effort is a major issue as privacy, ownership, funding, and use are all major concerns. Until now, this cooperation, which is a prerequisite for the success of roadside infrastructure deployment, as reported in [7], has remained largely unconsummated.

Funding Approaches

One of the most important stumbling blocks in infrastructure deployment is funding. The DoT long-term deployment plan, which envisioned 200,000–250,000 RSUs to be installed [4], potentially requires billions of dollars in investment. The current uncertain economic climate as well as the previously mentioned difficulties in justifying the benefits of this new technology and lack of a healthy cooperation between different organizations have crippled the initiative required for financing the deployment program.

It is interesting to note that most of the above reasons are *non-technical in nature*. Social, economic, and political issues are the major obstacles that have impeded the extensive deployment of RSUs. Since major collaborative efforts are necessary to resolve these issues, in this article, we propose an *alternative approach* to roadside infrastructure by leveraging the use of existing DSRC-equipped vehicles to provide *RSU functionality*. This approach employs a powerful self-organizing network paradigm, and draws its inspiration from social biological colonies such as ants, bees, birds, and fish. Such an approach was formulated for the first time in [8], where it was suggested that several fundamental transportation problems can be solved by carefully studying the behavior of self-organizing biological systems and applying the underlying principles of their successful operation to transportation problems. In [8], as an example of this approach, it was shown that vehicular traffic at intersections in urban areas can be managed by a new technology known as *virtual traffic lights* via the cooperation of vehicles at that intersection through V2V communications and without the need for infrastructure-based traffic control. In this article, we show that another acute transportation problem (the deployment of RSUs) can also be solved by using the same powerful approach.

Proposed Solution: Cars as RSUs

Inspired by social insect colonies such as ants, bees, and termites, we propose a self-organizing network solution that leverages the existing DSRC-equipped vehicles to be used as *temporary RSUs*. As a temporary RSU, a vehicle can make a brief stop and take on or assume the tasks of a conventional RSU — relaying messages to nearby vehicles and acting as a communication bridge for other vehicles in the network. The proposed solution consists of two main components, each of which addresses the following key questions:

- Which vehicles should act as temporary RSUs? How can a vehicle determine, in an independent and distributed manner, whether or not it should temporarily serve as an RSU?
- What are the tasks of temporary RSUs? What does a vehicle have to do while serving as a temporary RSU? How long should it continue to serve as an RSU?

Inspired by social insect colonies such as ants, bees, and termites, we propose a self-organizing network solution that leverages the existing DSRC-equipped vehicles to be used as temporary RSUs. As a temporary RSU, a vehicle can make a brief stop and take on or assume the tasks of a conventional RSU.

In order to answer the above questions, one needs to have a target application. Different applications may require different algorithms/solutions to the aforementioned questions. To demonstrate the feasibility of the proposed concept, a specific safety application, namely a post crash notification (PCN) application, is used in this article as an illustrative example to show how the proposed "poor man's solution," with zero infrastructure support, can help improve the network connectivity. The main purpose of the PCN application is to disseminate a safety message (i.e., information about the incident — time, location, etc. — which may be issued by a vehicle involved in the accident or a police car) to all vehicles within a region of interest (ROI), and the message should be disseminated to these vehicles within a short amount of time. The following subsection describes in detail how the proposed solution can be implemented.

Distributed Algorithm for Selecting a Temporary RSU

Figure 1a presents a simple example that provides important insights into how the RSU-selection algorithm should be designed. A flow diagram of the proposed algorithm is shown in Fig. 2.

Consider an example of a network as shown in Fig. 1a: the black, green, and blue squares and red circle represent vehicles, whereas arrows represent the movement direction of vehicles. Assume, with no loss of generality, that an accident takes place at the center of this network and vehicle *Src* involved in the accident sends out a post crash notification message (i.e., a safety message) to other vehicles in the network. After the first broadcast from *Src*, all vehicles in the gray-shaded region (i.e., the coverage poly-

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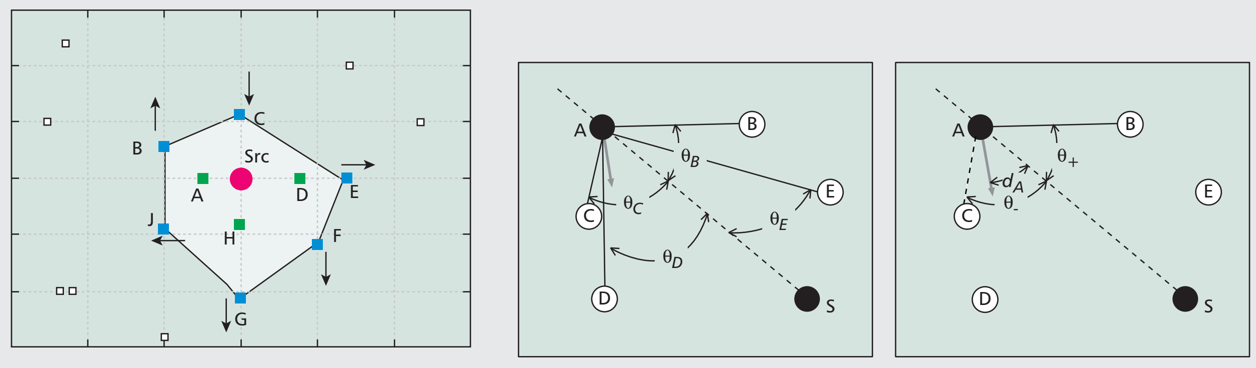
[4] Deployment cost of 5-1-1 system ranges from $133,000 to $1,028,000 [6].



(a) (b)

Figure 1. *a) Boundary of the network coverage polygon. Assume that the message is broadcast from Src at the scene of accident. Vehicles that are connected to Src via spatial relays are in the gray shaded region. Boundary and non-boundary vehicles are indicated with blue and green dots, respectively. Black squares indicate vehicles that do not receive spatial message broadcast from Src. Black arrows indicate current direction of the vehicles. b) The principle of operation of the proposed distributed gift-wrapping algorithm. Assume that the neighbor set of node A is* $NBR(A) = \{S, B, C, D, E\}$*, the moving direction of A is indicated by the gray arrow (in Fig. 1b), and A first receives the message from vehicle S [9].*

gon) receive the message and are informed about the accident. Note that the coverage polygon is the polygon that contains all vehicles that are informed via *spatial* relays from *Src* or other informed vehicles. In other words, the polygon contains all vehicles that could be reached from *Src* via either direct transmission or multihop forwarding. Based on the definition of the coverage polygon, the following observations can be made:

Observation 1: Good candidates for temporary RSUs are vehicles that are positioned at the boundary of the coverage polygon.

By definition, vehicles that are on the boundary of the network polygon have both informed and uninformed vehicles in their vicinity.[5] These vehicles are therefore highly likely to meet with other uninformed vehicles before other non-boundary and informed vehicles meet uninformed ones. The non-boundary and informed vehicles, on the other hand, are mostly surrounded by informed vehicles; hence, there is no additional benefit in having these vehicles serve as temporary RSUs. Figure 1a provides a simple example: the coverage polygon is shaded in gray, and blue and green rectangles represent boundary and non-boundary vehicles, respectively.

Observation 2: Only boundary vehicles that travel toward the accident should serve as temporary RSUs.

In addition to the position of vehicles, movement directions of these vehicles should also be considered as well. In this article, based on the mobility pattern assumed, we propose that only boundary vehicles that travel *toward* the accident should stop and serve as temporary RSUs. By having these vehicles stop at their current locations for a brief period of time (and not continue to travel toward the accident scene), the subsequent rebroadcasts from these vehicles could possibly reach other uninformed vehicles when they arrive in the RSUs' neighborhood. It should be noted that the boundary vehicles which travel in the outward direction from the scene of an accident *do not stop*; a message can be disseminated quickly through spatial relays of these vehicles that store, carry, and later forward (SCF) the message to vehicles in a region toward which these vehicles travel (i.e., this region is outside the coverage polygon). In Fig. 1a, only vehicle *C* (not vehicles *B*, *E*, *F*, *G,* and *I*) will act as a temporary RSU. In the remainder of this article, we refer to rebroadcast from temporary RSUs (e.g., vehicle *C*) as *RSU rebroadcasts* and rebroadcasts from other vehicles as *SCF rebroadcasts*.

In order to determine an accurate coverage polygon and its boundary, one needs global knowledge of the network (i.e., the location of all vehicles in the network). However, since such information requires excessive information exchange between vehicles (i.e., overhead), which is not desirable in VANETs, we use the distributed gift-wrapping algorithm proposed in [9]. This algorithm is a distributed algorithm; a vehicle, upon receiving a message, can determine independently and in a distributed manner whether it lies on the boundary of the coverage polygon. Note that since it only relies on the local information, the distributed gift-wrapping algorithm is only an approximate algorithm and tends to over-select boundary vehicles (i.e., some vehicles selected by the algorithm may not lie on the boundary of the polygon). More details about this algorithm can be found in [9]. In addition to the gift-wrapping algorithm, additional rules that consider directions of vehicles are added to the original distributed gift-wrapping algorithm. The resulting algorithm, Algorithm 1, is then used to select vehicles to serve as temporary RSUs.

Figure 1b illustrates how the temporary RSUs are selected by Algorithm 1. Upon receiving a message for the first time from vehicle *S*, vehicle *A* computes the angle π_i for all of its neighbors (Fig. 1b, left). Maximum (θ_+) and minimum (θ_-) angles are then identified. In the scenario given here, vehicles *B* and *C* are the neighbors of vehi-

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[5] *Vicinity in this case implies the nearby region and is not equivalent to the term* neighborhood.

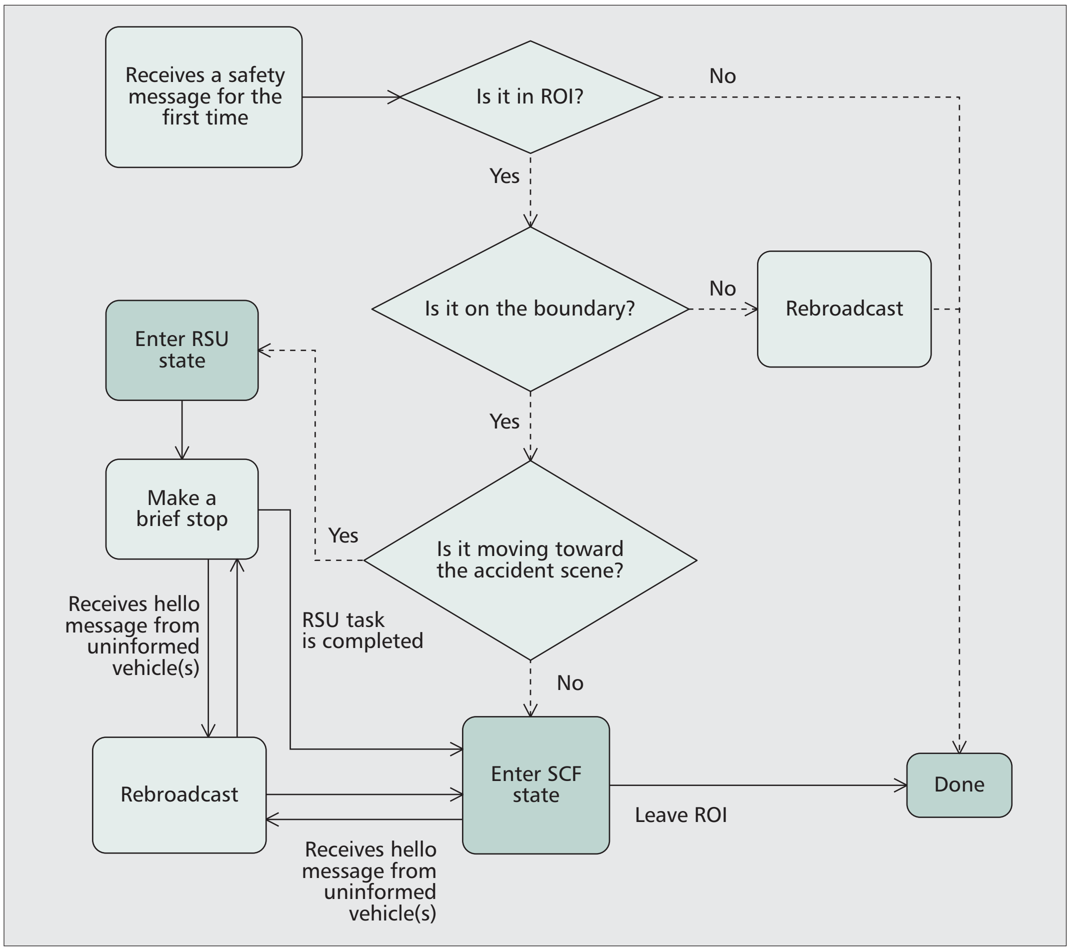

Figure 2. *Flow diagram describing the distributed algorithm for selecting a temporary RSU and the tasks performed by temporary RSUs.*

In the simulator, to maintain a constant vehicle density in the network, a new vehicle is immediately added to the network once a vehicle exits. We assume that this new vehicle is uninformed (i.e., it does not receive the safety message from prior rebroadcasts of the message).

cle *A* that have the maximum and minimum angles, respectively; and since $|\theta_+| + |\theta_-|$ is less than π and the moving direction of vehicle A falls between θ_- and θ_+, vehicle *A* is selected as a temporary RSU.

TASKS OF A TEMPORARY RSU

As shown in the flow diagram in Fig. 2, informed vehicles that are on the boundary of a coverage polygon and moving toward the scene of an accident act as temporary RSUs for a certain period of time. These vehicles make a brief stop and periodically rebroadcast the safety message to mimic the role of conventional RSUs. Vehicles that receive such message rebroadcast from these temporary RSUs (i.e., RSU-vehicles) follow the same procedure as shown in Fig. 2. It must be noted that when one considers a different (possibly non-safety) application such as instant messaging or content download, the tasks of temporary RSUs may be different — the temporary RSUs may stop for a different amount of time depending on the application; their stop duration may be preempted if the applications they support end; or, instead of rebroadcasting the safety message, they may need to forward the messages only to particular vehicle(s).

SIMULATION SETTING

The traffic mobility model used in the simulations is based on the CA-based mobility model developed in [10], and parameter values used in the simulations are summarized in Table 1. In the simulator, to maintain a constant vehicle density in the network, a new vehicle is immediately added to the network once a vehicle exits. We assume that this new vehicle is uninformed (i.e., it does not receive the safety message from prior rebroadcasts of the message).

TRAFFIC PATTERN

Based on the commuting pattern in highly populated cities such as New York City (NYC), we observe that the traffic pattern can be categorized into four categories:

- Morning rush hour traffic (8–10 a.m.)
- Lunch hour traffic
- Evening rush hour traffic
- Midnight traffic (1–3 a.m.)

In the mobility model used in this article, we assume the evening rush hour traffic, where most traffic travels in the northbound direction. We also assume that the scene of an accident is located at the top center of the network, and the safety message broadcast by the source should be disseminated to all vehicles in the region.

Parameters	Values
Size of the road structure	0.5 km × 0.5 km, 1 km × 1 km 2 km × 2 km, 3 km × 3 km
Length of a road block	125 m
Vehicle density	100 vehicles/km^2
DSRC penetration rate	{10%, 20%, …, 100%}
Simulation time	15 min (5-min warmup period)
Maximum speed	15 m/s (36 km/h)
Cycle duration	45 s
Green light ratio	50/50
Signal offset	10 s
Stop time of RSU vehicles	10–60 s

Table 1. *Parameter values for simulation study.*

TRANSMISSION RANGE

To take into account the possible obstruction of signal propagation due to buildings and high rises in urban cities, we assume two different types of communications: direct line-of-sight (LOS) and non-line-of-sight (NLOS) communications. LOS and NLOS have transmission ranges of 250 and 140 m, respectively. Any two vehicles can communicate directly (i.e., in single-hop fashion) if and only if they are within the corresponding transmission ranges. In addition, we assume accurate GPS information in our simulations (i.e., a vehicle has perfect knowledge of the positions of itself and all of its one-hop neighbors).

METRICS

In this article, two performance metrics are used to evaluate the advantages of the proposed solution. Since the post crash notification application is considered as an example in this article, the message reachability metric is used to indicate the message dissemination rate achieved by the proposed solutions, that is, the fraction of vehicles that are informed when the proposed solution is implemented. It should be mentioned here that improvement in network connectivity comes at the expense of a slight increase in travel time. Vehicles that act as temporary RSUs need to make brief stops, resulting in an increase in travel time. To capture such an effect, average velocity of vehicles is considered.

Message Reachability Metric — We use the message reachability metric to evaluate the performance of our scheme against the standard scheme (i.e., no vehicles stop and serve as RSUs). The message reachability metric is defined as the fraction of vehicles in the network that receive the message. Note that message reachability is different from network reachability metric. In other words, while the network reachability measures the maximum number of vehicles that are connected at a given point in time (i.e., a static metric),[6] message reachability is a transitive measure of network reachability [11].

Average Vehicle Velocity — Average vehicle velocity is used to capture how much the RSU's stop time affects the overall traffic flow in a city. Both average velocity of all vehicles and only those vehicles that act as temporary RSUs are reported.

SIMULATION RESULTS

The simulation results are shown in Fig. 3. Observe that the proposed cars as RSUs scheme considerably outperforms the standard scheme; with the proposed scheme, a message reaches almost twice the number of vehicles in the network (i.e., the message reachability improves from 34 percent to almost 67 percent in a 100 veh/km^2-dense network and 20 percent DSRC penetration rate, which corresponds to a 97 percent improvement).

Such an improvement is mainly due to the fact that with the Cars as RSUs scheme, vehicles that serve as RSUs stay in the network for a longer period of time (i.e., ratio of *informed* vehicles is higher), and since there are more informed vehicles (i.e., vehicles that have received the message), there are more message rebroadcasts that reach the *uninformed* vehicles (i.e., vehicles that have not received the message) with a higher probability. Note that the increase in network connectivity of the proposed scheme comes at the expense of a slight degradation in travel time (i.e., decrease in average vehicle velocity). Since vehicles make brief stops occasionally, our simulations have shown that velocity of a vehicle, on average, decreases by 0.27 km/h. This translates to a 1.48 percent decrease in average vehicle velocity and 1.51 percent increase in travel time. This, however, is a small increase compared to the increase in travel time due to accident-induced congestion. It is worth noting that although the proposed scheme might not significantly outperform the standard scheme, especially in the scenario with only 10 percent penetration rate, it is able to keep the safety message in the ROI for a long period of time (i.e., more than 300 s). Observe that with the standard scheme, the informed vehicles spend little time in the ROI and are likely to leave the ROI before they are able to rebroadcast the message to other uninformed vehicles. As a result, the message reachability decreases with time, and the message *dies out* after some time (i.e., 200 s after the first broadcast in our case).

Figure 3 (left) shows the reachability of networks with and without RSU vehicles for different DSRC penetration rates. Observe that significant improvement in terms of network reachability can be achieved when RSU vehicles are implemented only in a network with sparse and moderately dense DSRC-equipped vehicles (i.e., 10–40 percent penetration rate). The improvement is most pronounced in a moderately dense network (i.e., a network with a certain density). When a network has very few DSRC-

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[6] *Which is equal to the fraction of vehicles that belong to the largest connected component of a network*

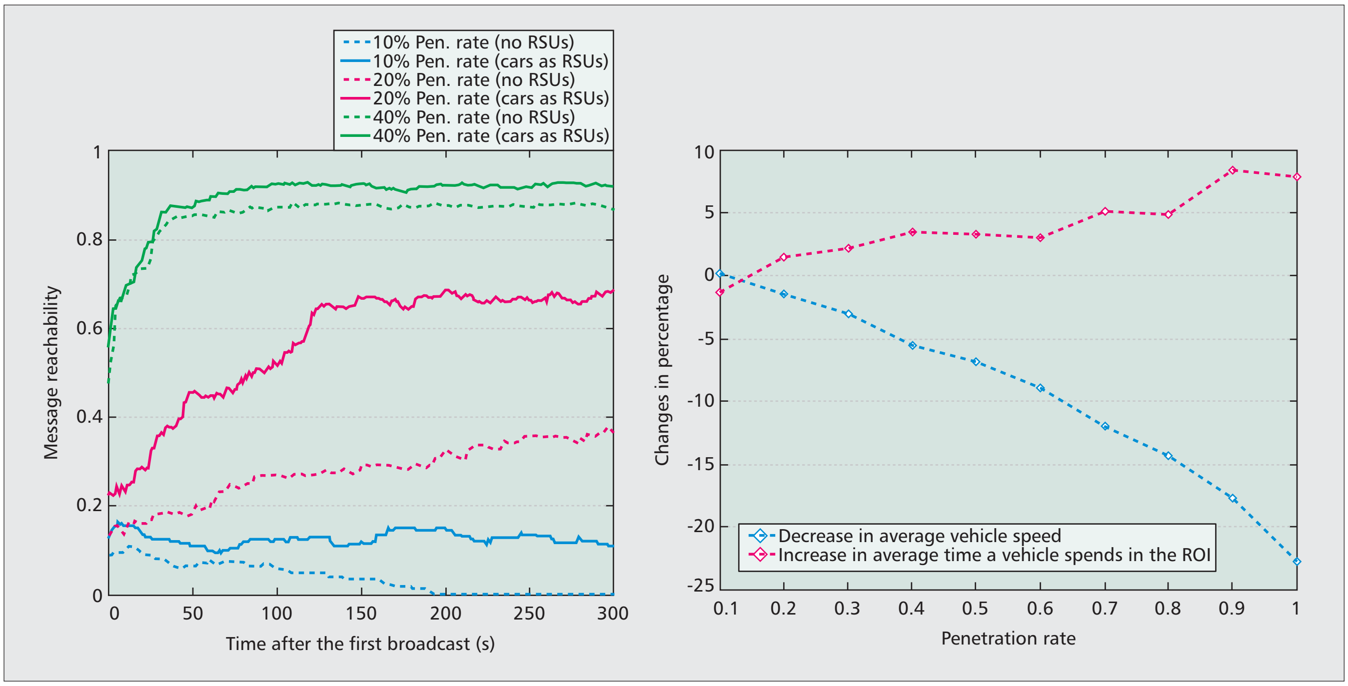

Figure 3. *Impact of vehicle density on the message reachability (left figure) and average vehicle speed and average time a vehicle spends in the ROI (right figure) when the proposed scheme is implemented. Substantial improvement is observed only in sparse and moderately dense DSRC-equipped networks. The results are based on a 1 km × 1 km ROI and 30 s RSU vehicle stop time.*

equipped vehicles, not much improvement is reported since an RSU's stop time may not be long enough for the temporary RSUs to encounter other uninformed vehicles. In addition, it should be noted that in a very sparse network, the coverage polygon (Fig. 1a) usually has a small size. Vehicles that act as temporary RSUs may be located very close to the accident. Although an uninformed vehicle receives a safety message from one of these RSUs, the message may no longer be useful as they are already close to the accident scene, having passed the last exit or alternative route that exists before driving into the congestion induced by the accident. On the other hand, when there are many DSRC-equipped vehicles in the network (i.e., a densely DSRC equipped network), the network is already well connected, and no vehicles need to act as temporary RSUs. By having some vehicles in a densely DSRC equipped network stop as RSUs not only degrades the message reachability but also impedes the overall traffic flow. Figure 3 (right) shows almost 8 percent increase in average time a vehicle spends in the ROI and 24 percent decrease in average vehicle speed when the network is dense.

While message reachability may increase with vehicle density (since dense traffic leads to a decrease in vehicle speed), our simulation results show that a change in the total number of vehicles in the network (i.e., density of equipped and unequipped vehicles combined) has far less effect on message reachability than the impact caused by a change in the number of DSRC-equipped vehicles.

EFFECT OF DIFFERENT PARAMETERS

EFFECT OF THE SIZE OF REGION OF INTEREST

Our simulation results show that the message reachability of both schemes decreases with the size of the ROI. This is due to the fact that the size of the coverage polygon (Fig. 1a) of networks with the same density *does not* change with the size of ROI. Since the message reachability metric is a relative measure, it follows that the fraction of vehicles in the coverage polygon (hence, message reachability) decreases when the size of ROI increases. In addition, when one considers additional rebroadcasts from the temporary RSUs, similar conclusions can be drawn: the number of uninformed vehicles that are informed by the rebroadcasts from these RSUs does not vary with the ROI size; hence, the message reachability is higher when the ROI size is small. For example, for a density of 100 veh/km^2, 20 percent DSRC penetration rate, and 30 s RSU vehicle stopping time, message reachability 2 min after the broadcast increases from 27 to 60.75 percent for 1 km × 1 km ROI, whereas for a 3 km × 3 km ROI, it increases from 6.39 to 15.35 percent.

EFFECT OF STOP TIME OF RSU-VEHICLES

Figure 4 shows the significant effect of stop time of RSU vehicles on message reachability. Observe that when the stop time is too short, the Cars as RSUs scheme gives comparable performance to the conventional scheme *without* RSU vehicles. This is because the RSU vehicles do not stop long enough to encounter other uninformed vehicles. As a result, the message reachability increases with the stop time until the stop time reaches a certain value (i.e., 30 s in this case). Any additional stop time beyond 30 s does not improve the message reachability because the RSU vehicles are unlikely to encounter uninformed vehicles after having stopped for some

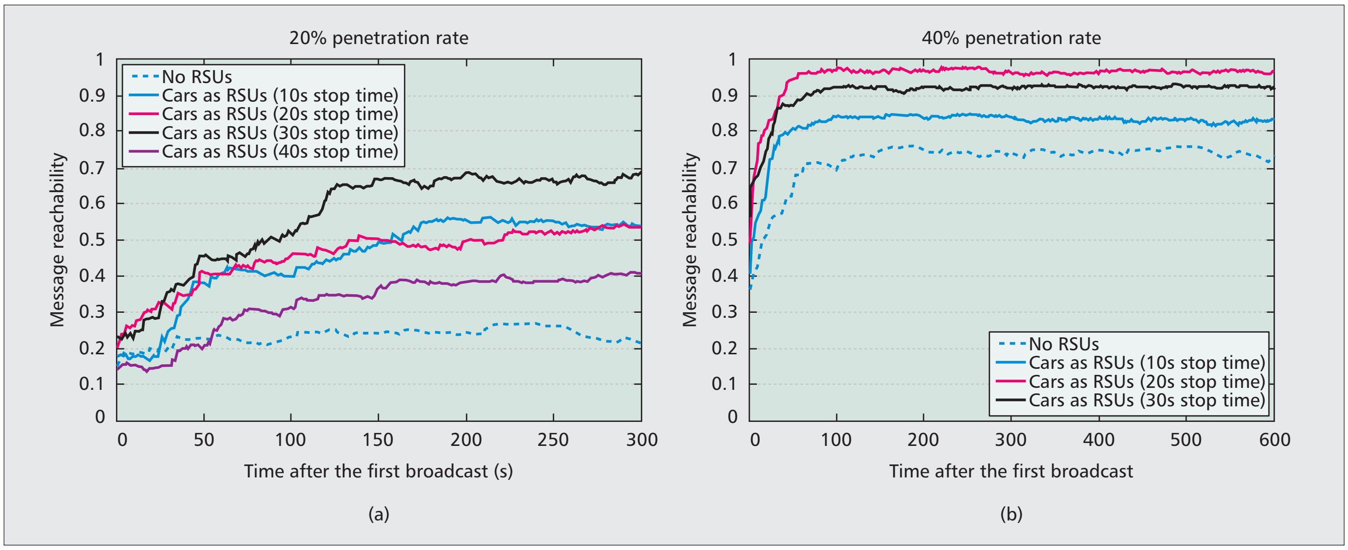

Figure 4. *Impact of the RSU-vehicle stop time on the message reachability of the network with and without RSU-vehicles. Substantial improvement is observed only in sparse and moderately-dense networks. The results are based on a 1 km x 1 km Region of Interest and vehicle densities of 100 veh/km2 with 20 percent and 40 percent DSRC penetration rates on the left and right figures, respectively.*

time (i.e., 30 s in this case). It is therefore more beneficial for these vehicles to continue to move and possibly further rebroadcast the message to uninformed vehicles in other areas in the region of interest. Note also that too large a stop time not only degrades message reachability, but also increases the travel delays of the vehicles that act as temporary RSUs. It is clear that the *optimal* stop time depends both on the vehicle density, size of the ROI, and topology of the network. While 30 s seems to be the optimal stop time for the network with 20 percent DSRC penetration rate (Fig. 4a), a smaller stop time (i.e., 20 s) would be needed for the maximum message reachability in a 40 percent DSRC penetration rate network (Fig. 4b).

EFFECT OF MOBILITY PATTERN

Figure 5 shows the significant effect of the mobility pattern of vehicles on message reachability. The proposed RSU vehicle scheme provides significant improvement when most of the traffic moves in a particular direction; as the fraction of northbound traffic increases, the improvement of the RSU scheme also increases. For example, when 85 percent of traffic is northbound, the message reachability increases from 34 to 67 percent, which corresponds to an improvement of 97 percent. This suggests that the proposed RSU scheme will work very well during rush hours. For example, during the evening rush hours in Manhattan, a large fraction of people commute from their workplaces downtown to their homes in the uptown area (i.e., dominant northbound traffic).

DISCUSSION

Consider the current way emergency situations are handled in urban areas; for example, if there is an ambulance or fire truck trying to reach an emergency area, all the vehicles on the road move to the side of the road, making way for the ambulance or fire truck to pass. This clearly delays all the vehicles agreeing to do this sacrifice as they slow down and move to the side of the road, which probably takes anywhere from 30–60 s. This collective sacrifice can save the life of a sick patient or people who are trapped in a building on fire. In this article, we use this example as a motivation for the proposed solution: a vehicle sending a safety message waits for an implicit acknowledgment (as opposed to an explicit acknowledgment) before continuing its trip. If the ACK is not received, the vehicle stops and keeps broadcasting the message until it receives an ACK (or until the scheduled broadcast duration ends). This way, the vehicle serves as a temporary RSU, thus enhancing the message reachability and network connectivity substantially.

The proposed system is extremely attractive due to its cost effectiveness and ubiquity, especially in the current environment where the deployment of roadside infrastructure is very limited. In a sense, the proposed solution is a “poor man’s solution” to a very real and acute problem, that is, the projected low penetration rates of DSRC technology at the initial stages of DSRC deployment. As such, the main idea behind the proposed solution is to exploit the self-organizing network characteristics of a vehicular network whereby the fleet of cars can solve a formidable problem by themselves through cooperation without additional equipment or infrastructure. By using certain vehicles as temporary roadside units, this temporary infrastructure could be provided ubiquitously without requiring additional equipment. This approach not only improves connectivity of vehicular networks in the early stages of DSRC development, but it can also accelerate the adoption of DSRC. For the successful operation of the proposed solution, the following issues will need to be addressed:

- Cooperation of state or local traffic management institutions (an example of this is Zipcar [12])

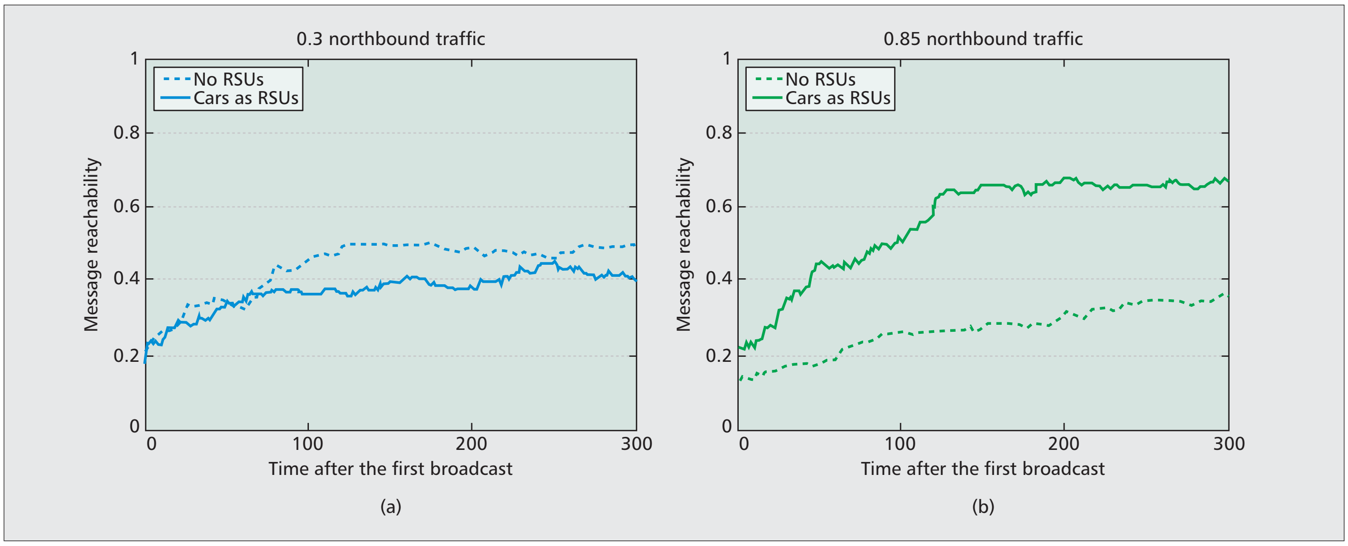

Figure 5. *Impact of the mobility pattern on the message reachability of the network with and without RSU vehicles. The improvement of the RSU vehicle scheme over the conventional scheme increases with the increase in northbound traffic. The results are based on a 1 km × 1 km ROI network with vehicle density of 100 veh/km^2, 20 percent DSRC penetration rate, and 30 s RSU vehicle stop time.*

- Guaranteeing correct and reliable operation against faults and/or malicious attacks
- Incentives or other mechanisms for policy enforcement

Our ongoing work is focused on addressing these issues.

While the cooperative approach presented here might appear altruistic for current day driving practices, it is not difficult to see that the presented approach could also be used by autonomous vehicles of the future. It is well known that companies like Google and several car manufacturers such as GM, Volkswagen, and Nissan are currently looking into autonomous vehicles as a potential new technology. The authors of this article believe that in the long run autonomous vehicles will have to use radios (e.g., DSRC radios or a similar communications technology) for V2V communications as this has tremendous benefits for even autonomous vehicles. The approach presented in this article could thus be used for autonomous vehicles as well, in which case human decisions will not be required, and a car selected to serve as an RSU will do this automatically.

RELATED WORK

A comprehensive comparison between different type of RSUs is presented in [13]. Both analytical and simulation results reveal that relay and mesh nodes, as opposed to base stations, can be more cost-effective solutions even though a much larger number of such units are required to deliver the same level of performance as offered by the base stations. In addition, the authors also suggest that adding a small amount of infrastructure is vastly superior to even a large number of mobile nodes capable of routing to one another.

An interesting paper by Trullols *et al.* [14] uses the approach employed by the maximum coverage problem for addressing this issue. The authors identify that roadside infrastructure should be placed at intersections rather than the middle of road segment. Two strategies for RSU placement locations are proposed: one that maximizes the number of vehicles served by RSUs, and another that maximizes the number and contact time between vehicles and RSUs. While the above studies are based on simulation data, a realistic trace of traffic is used to evaluate different schemes for RSU placement in [15]. The authors use a greedy algorithm to determine the minimum number and locations of RSUs that can serve all vehicles in Jeju, Korea.

Several studies address the issue of effective communications between vehicles and RSUs. For example, an RSU-based solution for a collision warning system (CWS) in urban areas is suggested in [16]. The authors propose an algorithm to determine when the RSUs installed at intersections should broadcast warnings to vehicles headed toward the intersection. Zhang *et al.* propose in [17] a scheduling scheme for RSUs to provide a balance between serving downloads and upload requests from fast-moving vehicles on highways. An interesting paper by Eckhoff *et al.* proposes utilizing parked vehicles as relay nodes to address the disconnected network problem. Extensive simulations and real life experiments show that parked cars can increase cooperative awareness by over 40 percent [18].

While the aforementioned studies shed light on the RSU placement problem, and the communications between vehicles and RSUs, it should be noted that, to the best of our knowledge, there are no existing studies on the use of vehicles as RSUs.

CONCLUSION

In this article, we propose a biologically inspired new approach to implementing roadside units. Instead of using a costly roadside infrastructure (e.g., RSUs) or high-packet-latency cellular networks and WiFi, we leverage the use of DSRC-equipped vehicles to serve as temporary roadside units. Based on the designed local rules, a DSRC-equipped vehicle independently determines whether it should serve as an RSU; and, if so, it stops for a small duration and rebroadcasts the message. Results show substantial improvement in terms of message reachability, which is crucial for safety message dissemination application in VANETs. It is worth mentioning that even though the benefits reported in this article are based on a specific safety application (post crash notification), our preliminary results show that the same concept could be used for other safety and efficiency applications of VANETs also.

It is worth mentioning that even though the benefits reported in this article are based on a specific safety application (Post Crash Notification), our preliminary results show that the same concept could be used for other safety and efficiency applications of VANETs also.

While the solution proposed to the RSU deployment problem is interesting in itself, perhaps even a more interesting universal conclusion is how the biologically inspired approach to solving fundamental transportation problems can be generalized and used as a powerful approach and tool for solving several important transportation problems. Our ongoing work is currently looking into other instances of the same approach for solving other outstanding transportation problems.

ACKNOWLEDGMENT

This research was supported in part by the T-SET University Transportation Center sponsored by the US Department of Transportation under Grant No. DTRT12-G-UTC11.

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