Cars as Roadside Units: A Cooperative Solution

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Abstract—**The gradual penetration of Dedicated Short Range Communications Radio (DSRC) technology in the years to come is a formidable problem that could adversely affect the implementation of safety and non-safety applications. In this paper, we propose a solution that might mitigate the negative impact of the partial and gradual penetration problem of DSRC technology. The proposed solution is based on a self-organizing network paradigm that draws its inspiration from biological systems, such as social insect colonies [1]. By designing the local rules and a distributed algorithm needed to perform this function, it is shown that DSRC-equipped cars can indeed serve as RSUs. Results show that the message reachability and connectivity in urban vehicular networks can be increased substantially in a cost-effective manner as the proposed approach does not entail deployment of infrastructure-based RSUs.**

I. Introduction

Successful deployment of vehicular ad hoc networks (VANETs) where information (such as traffic, road information or safety messages) is sent, forwarded, and received by vehicles depends on the adoption of a new wireless technology, namely the Dedicated Short Range Communications (DSRC) technology[2]. During the initial stage of DSRC deployment, two wirelessly-capable vehicles that are not within proximity of each other may communicate through Cellular networks [3], satellite, WiMax, etc. Infrastructure can therefore act as a bridge for vehicle-to-vehicle (V2V) communications. However, in addition to growing demand for V2X traffic[1] and the fact that V2V applications are constrained to a particular geographical area, installing special Roadside Units (RSUs) has emerged as an attractive solution (especially to the Department of Transportation) for providing infrastructure support since RSUs limit information to be disseminated to 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 and the need for cooperation between public and private sectors seem to be major obstacles for the large-scale deployment of RSUs. For example, a simplistic form of RSU (such as Roadway Probe Beacons) requires $\$13,000 - 15,000$ per unit capital cost and up to $\$2,400$ per unit per year[2] for operation and maintenance[4]. In addition to cost, effectiveness and utilization rate of RSUs may also depend on the number of DSRC-equipped vehicles that are present in a given area.

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

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

In this paper, based on a biologically-inspired networking paradigm [1], we propose to leverage the existing 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. We envision that using vehicles as RSUs could improve not only the message reachability and network connectivity but also accelerate the adoption of DSRC technology in addition to avoiding the cost of deploying Roadside Units.

The remainder of this paper is organized as follows. Section II formulates the problem after providing the necessary background relevant to this subject. The proposed solution is described in detail in Section III. Simulation setting and the preliminary performance evaluation of the proposed protocol are presented in Section IV, respectively. Related work is discussed in Section V. Finally, conclusions are drawn in Section VI.

II. Problem Formulation

Since it is envisioned that vehicle-to-infrastructure (V2X) applications might be the first applications that can be realized and that infrastructure is required for accelerating the adoption of the DSRC technology, the U.S. Department of Transportation (DoT) was expected to have a nationwide deployment of roadside infrastructure in 2008 [5]. This vision, however, did not materialize and, to date, very few RSUs have been deployed. Major reasons that prevented the success of the plan can be summarized as follows:

- Difficulty in determining benefits of RSU deployment. Due to the *novel* and *innovative* nature of the DSRC technology, wide adoption by the market is necessary so that the full benefits of the technology can be realized. Note also that such economic justification becomes more difficult when some roadside infrastructures for displaying traffic information such as Dynamic Message Sign (DMS) and 5-1-1 System already exist [6].
- Continuous cooperation and coalition of the public (e.g., federal agencies, city authorities, etc.) and private (e.g., car manufacturers and other companies) sectors are needed. As reported in [7], until now such cooperation has remained unconsummated.
- Adequate financial investment is one of the major obstacles in the wide deployment of roadside infrastructure as billions of dollars of investment is required for the installation of $200,000 - 250,000$ roadside units [5].

Note that while the above stumbling blocks are mostly *non-technical in nature*, in this paper, we propose an *alternative solution* that does not require global cooperation between public and private sectors and/or billions of dollars of investment.

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In other words, the proposed approach leverages 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 insect colonies such as ants, bees, etc.

III. Proposed Solution: Cars as RSUs

The proposed solution 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. While different applications may require different algorithms/solutions for selecting which vehicles should serve as RSUs, in this paper, we use the Post Crash Notification (PCN) application to demonstrate the feasibility of the proposed concept. 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 subsections describe in detail how the proposed solution can be implemented.

A. Distributed algorithm for selecting a temporary RSU

Figure 1 presents a simple example that provides important insights into how the RSU-selection algorithm should be designed. Consider an example of a network as shown in Figure 1; black, red, and blue squares and magenta circles represent vehicles whereas arrows represent movement direction of vehicles. Assume, with no loss of generality, that an accident takes place at the center of this network and the 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 polygon) 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 either via direct transmission or via multi-hop forwarding.

In order to determine an accurate coverage polygon and its boundary, one needs global knowledge of the network (i.e., location of all vehicles in the network). However, since such information requires excessive information exchange between vehicles which is not desirable in VANETs, we use a distributed gift-wrapping algorithm that first proposed in [8]. 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 local information, the distributed gift-wrapping algorithm is only an approximate algorithm and it tends to over-select boundary vehicles (i.e., some vehicles selected by the algorithm may

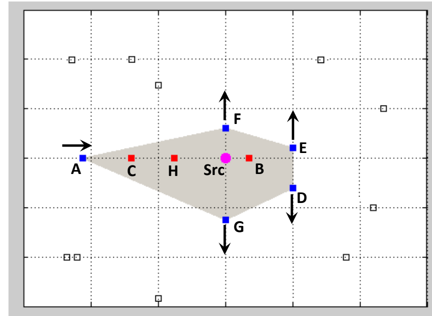

Fig. 1. Boundary of the network coverage polygon. Assume that the message is broadcasted from *Src* at the scene of accident. Vehicles that are connected to *Src* via spatial relays are in the gray shaded region. Boundary and non-boundary vehicles are indicated with blue and red dots, respectively. Black squares indicate vehicles that do not receive spatial message broadcast from *Src*. Black arrows indicate current direction of the vehicles.

not lie on the boundary of the polygon). More details about this algorithm can be found in [8]. In addition to the gift-wrapping algorithm, additional rules that consider directions of vehicles are added to the original distributed gift-wrapping algorithm; for example, only vehicles that travel toward the scene of accidents act as temporary RSUs.

B. Tasks of a temporary RSU

Informed vehicles that are on the boundary of coverage polygon and moving toward the scene of 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 the conventional roadside units. It must be noted that when one considers a different (possibly non-safety) application such as instant messaging, content download, etc, the tasks of temporary RSUs may be changed - 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 to only particular vehicle(s).

IV. Simulation Setting and Results

Traffic mobility model and transmission ranges used in the simulations are based on the CA-based mobility model and transmission pattern developed in [9]. A 1 km $\times 1$ km Manhattan grid topology with 125-meter road block is assumed and parameter values used in the simulations are summarized in Table I. 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).

In addition, we assume the evening rush hour traffic where most of traffic travel in northbound direction. We also assume that the scene of accident is located at the top-center of the network and the safety message broadcasted by the source should be disseminated to all vehicles in the region.

To take into account the possible obstruction of signal propagation due to buildings and highrises in urban areas, we

TABLE I
PARAMETER VALUES FOR SIMULATION STUDY.

Parameters	**Values**
Size of the road structure	1km $\times$ 1km
Length of a road block	125 meters
Vehicle density	100 veh/km^2
DSRC penetration rate	20%
Simulation time	15 minutes (5-minutes warmup period)
Maximum speed	15 m/s (36 km/h)
Cycle duration	45 seconds
Green light ratio	50|50
Signal offset	10 seconds
Stop time of RSU-vehicles	30 seconds

assume two different types of communications: direct line-of-sight (LOS) and a non line-of-sight (NLOS) communications. LOS and NLOS have transmission ranges of 250 and 140 meters, 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 positions of itself and all of its one-hop neighbors).

A. Metrics

In this paper, two performance metrics are used to evaluate the advantages of the proposed solution.

1) Message Reachability Metric: We use message reachability metric to evaluate the performance of our scheme against the standard scheme (i.e., no vehicles stop and serve as RSUs). Message reachability metric is defined as the fraction of vehicles in the network that receive the message. Note that the 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)[3], message reachability metric is a *transitive* measure of network reachability [2].

2) Average vehicle velocity: Average vehicle velocity is used to capture how much the RSU's stop time affect the overall traffic flow in a city. Both average velocity of all vehicles and only those vehicles who act as temporary RSUs are reported.

B. Simulation Results

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

Such an improvement is mainly due to the fact that with the proposed RSU scheme, vehicles that serve as RSUs stay in the network for a longer period of time (i.e., ratio of *informed* vehicles, e.g., network connectivity ratio, is higher) and since there are more *informed* vehicles (i.e., vehicles that have received the message), there are more message rebroadcasts which 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). This is shown in Table I. Since vehicles make brief stops occasionally, our simulations have shown that velocity of the vehicle, on average, decreases by 0.27 km/h. This translates to a 1.48% decrease in average vehicle velocity and 1.51% increase in travel time. This, however, is a small increase as compared to the increase in travel time due to accident-induced congestion.

[3]which is equal to the fraction of vehicles that belong to the largest connected component of a network

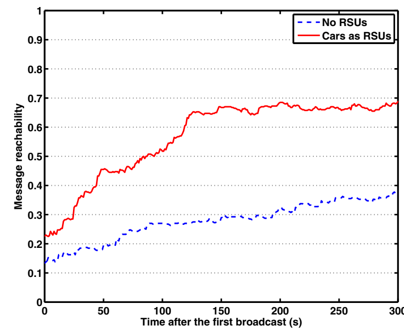

Fig. 2. Comparison in terms of network connectivity of our proposed scheme and the standard scheme that does not assume any RSU-vehicles. The results are based on a 1 km x 1 km Region of Interest, 100 veh/km^2 vehicle density with 20% DSRC penetration rate, and 30 secs RSU-vehicle stop time.

TABLE II
AVERAGE VEHICLE SPEED AND AVERAGE TIME VEHICLE SPENDS IN ROI WHEN THE PROPOSED SCHEME IS IMPLEMENTED. THE RESULTS ARE BASED ON A 1 KM X 1 KM REGION OF INTEREST, 100 VEH/KM^2 VEHICLE DENSITY WITH 20% DSRC PENETRATION RATE, AND 30 S OF RSU-VEHICLE STOP TIME.

Metrics	No RSUs	Cars as RSUs	% increase
Average speed (km/h)	18.08	17.81	-1.48%
Average time spent in ROI (min)	2.87	2.91	1.51%

Figure 3 shows the reachability of networks with and without RSU-vehicles for different DSRC penetration rate. 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., $10\% - 40\%$ penetration rate). The improvement is most pronounced in moderately-dense network; i.e., a network with a certain density. When a network has very few DSRC-equipped vehicles, not much improvement is reported since 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 (see Figure 1) 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 the uninformed vehicle is 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 DSRC-equipped-dense network), the network is already well-connected and no vehicle is needed to act as temporary RSUs. By having some vehicles in a DSRC-equipped-dense network stop to serve as RSUs not only degrades the message reachability but also impedes the overall traffic flow. Simulation result shows almost 8% increase in average time a vehicle spends in the ROI and 24% decrease in average vehicle speed when the network is dense.

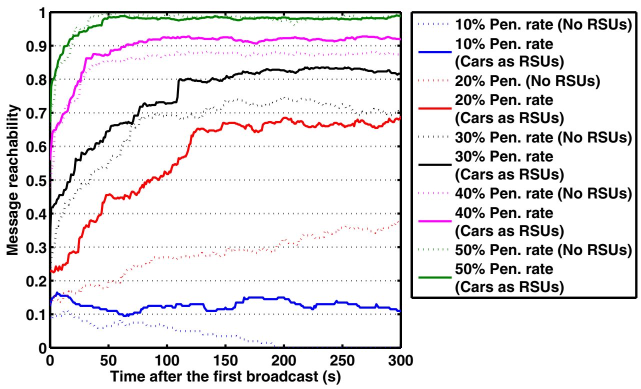

Fig. 3. Impact of DSRC penetration rate on the message reachabilitywhen the proposed scheme is implemented. Substantial improvement is observed only in sparse and moderately-dense DSRC-equippped network. The results are based on a 1 km x 1 km Region of Interest and 30s of RSU-vehicle stop time.

V. Related Work

While there are, to the best of our knowledge, no existing studies on the use of vehicles as temporary RSUs, the following studies seem somewhat relevant:

A comprehensive comparison between different type of RSUs is presented in [10]. 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. An interesting paper by Trullols et al. [11] 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. While the above studies are based on simulation data, a realistic trace of traffic is used to evaluate different schemes for RSU placement in [12]. The authors use a greedy algorithm to determine the minimum number and locations of RSUs that can serve all vehicles in Jeju city, Korea.

Several studies address the issue of effective communications between vehicles and RSUs. An RSU-based solution for Collision Warning System (CWS) in urban areas is reported in [13]. The authors propose an algorithm to determine when the RSUs installed at intersections should broadcast warnings to vehicles proceeding to the intersection. Zhang et al. propose in [14] a scheduling scheme for RSUs to provide a balance between serving downloads and upload requests from fast-moving vehicles on highways.

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

VI. Conclusion

In this paper, we propose a biologically inspired solution to the partial penetration problem of DSRC radios at the initial stages of deployment. The proposed approach draws its inspiration from self-organizing biological systems (such as ants, fish, and birds). More specifically, instead of using a costly roadside infrastructure (such as 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 and the new algorithm, 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 in VANETs. While a specific safety application is used to demonstrate the advantages of the proposed scheme, our preliminary results show that the same concept could be used for other VANET applications as well.

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