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***Abstract*—In this paper, we propose a novel optimization framework for Roadside Unit (RSU) deployment and configuration in a vehicular network. We formulate the problem of placement of RSUs and selecting their configurations (*e.g.* power level, types of antenna and wired/wireless back haul network connectivity) as a linear program. The objective function is to minimize the total cost to deploy and maintain the network of RSU's. A user specified constraint on the minimum coverage provided by the RSU is also incorporated into the optimization framework. Further, the framework also supports the option of specifying selected regions of higher importance such as locations of frequently occurring accidents and incorporating constraints requiring stricter coverage in those areas. Simulation results are presented to demonstrate the feasibility of deployment on the campus map of Southern Methodist University (SMU). The efficiency and scalability of the optimization procedure for large scale problems are also studied and results shows that optimization over an area with the size of Cambridge, Massachusetts is completed in under 2 minutes. Finally, the effects of variation in several key parameters on the resulting design are studied.**

I. Introduction

Vehicular networks are being used for a plethora of applications including enabling automotive safety [1]. Intelligent transportation systems can also leverage these vehicular networks to enable applications such as traffic congestion prediction, mitigation and dissemination. Inter-vehicle communication (IVC) systems can work in completely infrastructure-free manner, without support from a backbone network. IVC systems can be categorized into single-hop and multi-hop IVCs (SIVCs and MIVCs) [2]. Despite the zero infrastructure cost, the performance of SIVC and MIVC systems are limited by the short communication range and routing issues such as delay and incorrect routing. To overcome these limitations and enable information sharing with all users in the network, vehicles can connect to a roadside infrastructure [3]. In a roadside-to-vehicle communication (RVC) system, all communications are between on-board units (OBUs) and roadside units (RSUs), leading to quick and reliable transmissions within the network [4]. However, the number of RSU required could be relatively high, which requires higher cost associated with their deployment and maintenance. Therefore, in communication systems that involve roadside infrastructure, it is highly desirable to ensure reliable coverage in a cost efficient manner. Hybrid vehicular communication (HVC) systems offer a trade-off between IVC and RVC, extending the range of RVC by using vehicles as mobile routers [2].

In this paper, we develop a framework for the optimal deployment of both RVC and HVC networks. This paper studies the deployment of the roadside infrastructure by formulating it as an optimization problem and solving it using integer linear programming. The main contributions of the paper are as follows:

- We study the optimal placement and configuration of RSUs in 2-D vehicular networks. RSU locations are selected from a set of candidate locations specified by the user and typically include all intersections in the map. RSU Configuration includes transmit power level, antenna type (omni-directional or directional) and backbone network connectivity options (such as wired or wireless) used at each RSU in the network. Each RSU in the network can individually select optimal configuration settings based on its surrounding environment, traffic density, network connection offerings and the overall cost.
- The problem of obtaining an optimal RSU deployment is formulated as an integer linear program (ILP) and solved using the CPLEX solver. Due to the high cost of deploying and maintaining RSUs, the optimization aims to find a trade-off between network coverage and cost. In other words, the optimization framework allows the computation of the minimum cost of roadside infrastructure required to satisfy the user specified coverage requirements.
- The proposed optimization framework takes into account the effect of buildings on signal propagation, the effect of LAN lines on the RSU network solutions and the effect of road topology on the RSU antenna configurations. The framework also allows the user to specify spatial regions and temporal instances of higher importance and include a higher coverage requirement in those cases. For instance, intersections with a high historical accident rate could have more stringent coverage requirements. Further, different traffic models that correspond to the different traffic conditions during a day, such as ”Peak”, ”Normal” and ”Night” are included in the framework.

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- Simulation results quantify the non-linearities that exist between the cost and various system parameters. For example, the cost only increases by about 24% if the RSU coverage requirement increases from 20% to 80%. However, the cost rapidly grows by about 66.3% when the RSU coverage increases from 80% to 100%. Similarly, the cost drops by about 73% if we allow HVC with up to 2 vehicle-to-vehicle (V2V) hops instead of limiting to only RVC, but the cost reduction slows down dramatically as the maximum number of V2V hop allowed increases beyond 2. Depending on the application, these non-linear relationship could be leveraged by the network designer to artfully trade-off the cost and system performance.
- The scalability of the algorithm is also studied. We change the simulation parameters including the size of the map and number of realizations used for optimization. The network performance and runtime are used to demonstrated the scalability of the scheme. It can be shown that it takes only about 1.5 minutes to optimize the deployment for a map as large as the area of Cambridge, Massachusetts, and achieves 93% RSU coverage.

The remainder of this paper is organized as follows. In Section 2, we present related work on vehicular networks. Section 3 presents the problem formulation for the deployment of a hybrid vehicular communication infrastructure. In Section 4, we present simulation results that demonstrate the performance of the proposed optimization in several scenarios.

II. Related work

Roadside infrastructure plays an important role in VANETS, especially in the rollout phase of VANETs when only a few cars would have necessary equipment. It is pointed out that information dissemination is not practically feasible without taking advantage of RSUs [5]. Other than information dissemination, roadside infrastructure also brings in significant improvement in the connectivity [6], [7], routing [8] and transmission delay [9] of the communications.

Due to the static characteristic and the relatively high cost of the RSUs, a smart deployment plan is of significant importance for constructing an economical, energy-efficient and also reliable vehicular network. Various studies on VANETs provide basics for deployment design of roadside infrastructure. Considering both movement of vehicles and multi-hop forwarding, an analytical model is developed to study the spatial propagation of information in VANETs [10]. The model can be used to develop a placement strategy where the average delay in the network is bounded by a certain threshold. Some researchers also study the RSU position in the network. [11] suggests placing the RSU in the center of intersections instead of corner, which results in 15% increase in coverage area. Isolated vehicles can be avoided by placing the RSU at the middle of the road segments [7].

With better understanding of the communication system in VANETS, RSU placement strategies have attracted increasing attention from researchers. By evaluating the centrality and density of the network, strategies and hypothesis of RSU placement are given in [12]. Abdrabou et al statistically study the max distance between RSUs to achieve delay requirement in a 1-D VANET [9], [13]. Optimization of RSU deployment for 2-D VANETs is also developed, where vehicles can reach RSU within maximum driving time and overhead time [14]. By optimally deploying the roadside infrastructure, a variety of objectives can be achieved, such as maximizing the throughput and minimizing travel times [15], [16], [17].

Despite the aforementioned researches on optimal placement of RSUs, no study in the literature optimizes the configurations and placement of the RSUs jointly. In this paper, the deployment of roadside infrastructure is optimized such that individual RSU can have different configurations to achieve the overall objective of the network design. Further, the objective of the optimization problem is to minimize the cost subject to satisfying the coverage requirement. The coverage requirement is defined as the percentage of streets in the area that are within the service range of RSUs. Unlike [17], which maximize the number of vehicles traveling with the range of RSUs without considering delay, we take into account the maximum transmission delay and only consider cars that are in the service range within the delay. This assumption is important for safety related applications due to its time sensitive nature.

III. System Modeling

In this section, we formulate the problem of optimal RSU placement and configuration. The primary constraint is that the RSUs should cover a minimum desired percentage of streets. We allow multi-hop communications between vehicles with a limit on the maximum number of hops. This upper limit could be due to the maximum delay requirement imposed by a safety application. Our objective is to minimize the cost while satisfying all the requirements.

A. *Sets used in the model*

In this paper, the two-dimensional map of the coverage area is represented by a Cartesian coordinate system. All the horizontal streets are parallel to the x-axis, and all vertical streets are parallel to the y-axis. Street curvature is approximated by a piecewise linear model. Long streets are divided into several short segments in the model. For simplicity, it is assumed that candidate RSUs location are at all intersections and the end points of the short road segments. Therefore, dividing long streets into shorter segments can better approximate the real map, and also provides more RSU placement choices. However, more street segments result in a larger problem size, and increase the computational complexity of the optimization problem.

Let sets S, C and P represent, respectively, the set of street, candidate RSU locations and possible transmit power levels. We use the notation $|X|$ to represent the cardinality of set X. The set, A, contains the type of antennas that can be used at each RSU. These antennas can be omni-directional or directional with different orientations and down tilts.

The proposed framework considers multiple temporal traffic realizations in the optimization representing for instance, different times of the day such as rush hour, weekends and night time. Set R denotes the index set of random traffic realizations specified by the user. Let sets V_r for each $r \in R$ represent the random locations of the vehicles in realization r generated according to a predefined probability distribution. Depending on the application, it is likely that the requirement of each scenario differs. Vector $\mathbf{r}$ of size $|R|$ specifies the coverage requirement of each realization.

To demonstrate the ability of the framework to include spatial locations with increased coverage requirements, we define the set of intersections with high accident rate, $C_{accident}$ and specify the coverage requirements of these intersections by δ. In our numerical simulations we set $\delta = 100\%$.

B. Parameters used in the model

As noted before, we consider the design of both purely RVC and HVC systems. Parameter n_{hops} denotes the maximum number of inter-vehicular hops that data can be transmitted over before reaching a RSU. Setting $n_{hops} = 0$ results in a purely RVC network.

Incidence matrix I is a five-dimensional matrix, where $I_{i,j,k,m,n} = 1$ iff street $i \in S$ can be covered by setting up a RSU at location $j \in C$ using antenna type $k \in A$ and power level $m \in P$ in the realization $n \in R$. To compute the incidence matrix for a given antenna type, power level and realization, first, for each vehicle $i \in V_r$, we calculate the RSU locations which can communicate directly with vehicle i without V2V communications. This information is represented by a two-dimensional matrix D, where $D_{i,j} = 1$ iff vehicle $i \in V_r$ can direct communicate with the RSU at location candidate $j \in C$. Second, a $N_{veh} \times N_{veh}$ matrix H is used to determine intervehicle connectivity, *i.e.*, $H_{i,j} = 1$ iff vehicle $i \in V_r$ can directly communicate with vehicle $j \in V_r$. Third, for each street, in order to ensure the RSU at a particular location can cover the entire street, we add two *virtual* vehicles at the two ends of the streets. We assume that a RSU is able to cover a particular street if the RSU is able to communicate with both virtual vehicles using fewer than n_{hops} number of hops.

The additional feature of having mandatory RSU locations is specified by incidence matrix K such that $K_{i,j} = 1$ iff the RSU at location $j \in C$ can cover the high accident intersection $i \in C_{accident}$. The value of the matrix is determined by d, the range within which a RSU must be built from the intersection with frequent accidents. With a small value of d, a unique location results for the mandatory RSU location.

The cost of setting up a RSU at each location with certain transmission power level is specified by matrix m of size $|C| \times |P|$. This cost represents the amortized cost of installing and operating the RSU over a certain specified period of time. In real systems, a RSU can be connected to a backbone network using either a wired LAN or a wireless link. Consequently, the costs associated with two methods vary depending on the location. In the numerical results, we consider that the cost of using a wired LAN is an affine function of the distance between the RSU location and the LAN lines. Further in the numerical results, the cost of adding a wireless link to the backbone network is fixed. Note however, that certain RSU's may have only 1 possible connectivity option.

C. Decision variables used in the model

Binary variable $x_{i,j,k} = 1$ iff RSU at location $i \in C$ is activated using antenna $j \in A$ and power level $k \in P$. For convenience of notation, we also define binary variable $y_i = 1$ and $z_{i,k} = 1$ iff location i is chosen for setting up RSU using transmission power level k. The relationship between the variables x ,y and z is given in (3) and (4). Binary variable $h_{i,j}$ reflects the RSU coverage in each realization,*i.e.*, $h_{i,j} = 1$ iff street $i \in S$ is covered in realization $j \in R$.

D. The optimization framework

The optimization problem of interest is posed as:

$$\min_{x, y, z, h} \quad \sum_{i=1}^{|C|} \sum_{j=1}^{|P|} m_{i,j} z_{i,j} \tag{1}$$

$$\text{subject to constraints} \quad (2) - (7)$$

It can be clearly seen that (1) is an a integer linear programming problem and can be solved by any commercial LP solvers. We now elucidate each of the constraints in (2)-(7).

i) One antenna and one power level at each RSU location
For each candidate of RSU location, there should be at most one type of antenna installed and one level of transmission power chosen, *i.e.*,

$$\sum_{j=1}^{|A|} \sum_{k=1}^{|P|} x_{i,j,k} \leq 1, \quad \forall i = 1, \ldots, |C|. \tag{2}$$

ii) Relationship between variables x and y

$$\sum_{j=1}^{|A|} \sum_{k=1}^{|P|} x_{i,j,k} = y_i \quad \forall i = 1, \ldots, |C|. \tag{3}$$

iii) Relationship between variables x and z

$$\sum_{j=1}^{|A|} x_{i,j,k} = z_{i,k} \ \forall i = 1, \ldots, |C|, \text{and } k = 1, \ldots, |P|. \tag{4}$$

iv) Relationship between I and h
Street $i \in S$ can be covered in realization $n \in R$ iff street i can be covered by one or more than one selected RSU candidates using one or more than one selected antenna type and power level. The corresponding constraint is given by

$$\sum_{j=1}^{|C|} \sum_{k=1}^{|A|} \sum_{m=1}^{|P|} I_{i,j,k,m,n} x_{j,k,m} \geq h_{i,n}, \tag{5}$$

where $i = 1, \ldots, |S|$ and $n = 1, \ldots, |R|$.

v) RSU coverage
For every realization, the number of streets that are covered

by the RSUs should be greater than the specified requirement, which is expressed as,

$$\sum_{i=1}^{|S|} h_{i,j} \geq r_j, \ \forall j = 1, \ldots, |R|. \tag{6}$$

vi) Mandatory RSU coverage at frequent accident intersections

$$\sum_{j=1}^{|C|} K_{i,j} y_j \geq \delta = 1, \forall i = 1, \ldots, |C_{accident}|. \tag{7}$$

IV. Experimental Evaluation

In this section, we evaluate the performance of the proposed optimization method by simulations. We first describe the problem using AMPL and then use the CPLEX solver to generate a RSU deployment. Evaluation of this configuration is then performed using independently generated traffic scenarios. We also experimentally study the trade-off between the cost and performance of the roadside infrastructure as certain key system parameters are varied.

A. RSU coverage capability

In our simulation, we use the campus map of Southern Methodist University (SMU) in Dallas, Texas as the area of interest for the deployment, as shown in Fig. 1. We generate random traffic for each realization based on Poisson distribution, with mean and variance λ of each street according to statistics for different traffic conditions. The length for the street between two candidates of RSU location is 200m. There are four intersections with high accident rate as shown in the map.

We consider three traffic conditions: peak (high traffic density), normal (medium traffic density), night (low traffic density). Due to the different traffic condition, the requirements for the RSU coverage are different. In the simulations, we assume the coverage requirements for the peak hours, the hours of normal traffic and night hours are 100, 95 and 90 percent respectively. For each traffic density, we generate 10 realizations with random traffic.

There are three types of antennas available in the simulation, including omni-directional antenna and directional antenna with vertical and horizontal orientation, *i.e.*, $|A| = 3$. Options of transmission level, P_{TxOBU}, include -6dBm, -8dBm and -10dBm. For each RSU we assume that both a wired LAN and wireless link are available to provide connection to the backbone network. For each intersection with high accident rate, a RSU must be set up within distance $d = 200$m.

Other parameters are as follows: the max number of hops $n_{hop} = 2$, cost of wired LAN connection per meter $cost_{LAN} = 1$ unit, cost of setting up wireless link to the backbone $cost_{Wireless} = 1000$ unit, cost of transmission power $cost_{power} = [200, 150, 100]$ for power level of -6dBm, -8dBm and -10dBm respectively and minimal receive power of RSU and OBU $P_{RxRSU} = P_{RxOBU} = -60$dBm. Since we focus on the configuration design of roadside infrastructure, we assume only one transmission power level for all OBUs. Further, since most of the RSUs are battery operated, we assume the transmission power of RSUs is always lower than that of OBUs'. Here, the transmission power of OBU $P_{TxOBU} = -6$dBm.

We use the dual-slope piecewise-linear model [18] to calculate the path loss. The antenna gain G_t and G_r are normalized to be 1. The reference distance d_0 and critical distance d_c are 10 meters and 100 meters respectively. The path loss exponents γ_1 and γ_2 are 2.75 and 3.8 respectively. The formula of this model is given as

$$P(d) = \begin{cases} P(d_0) - 10\gamma_1 \log_{10}(\frac{d}{d_0}) & \text{if } d_0 \leq d \leq d_c \\ P(d_0) - 10\gamma_1 \log_{10}(\frac{d_c}{d_0}) - & \\ \quad 10\gamma_2 \log_{10}(\frac{d}{d_0}) & \text{if } d \geq d_c \end{cases} \tag{8}$$

where $P(d_0) = 20\log_{10}(d_0) + 20\log_{10}(f) + 20\log 10(\frac{4\pi}{c}) - 10\log_{10}(G_t G_r)$ and the operating frequency band f is 5.9GHz, as specified by FCC for DSRC(dedicated short-range communications). For simplicity, we assume that the concrete wall will introduce 8dB loss.

Based on the channel model and simulation parameters, the communication range for the RSU with omni-directional antenna is 309, 274, and 243 meters with different transmission powers. With directional gain of $4dB$, the RSU with directional antenna has communication range of 394, 349, and 309 meters. Vehicles are equipped with omni-directional antennas with communication range of 309 meters.

The algorithm solves the optimization problem and generates the roadside infrastructure by fulfilling the RSU coverage requirement in all the realizations. The roadside infrastructure output by the optimization scheme is shown in Fig. 1. There are 10 RSUs placed, with seven of them using omni-directional antennas and others using directional antennas. Variation of radius in RSU coverage indicates different levels of transmission power are employed, with two RSUs using -6dBm, one RSU using -8dBm and the rest using -10dBm. It is worth pointing out that only one RSU is connected with a wireless link because most of the RSUs are relatively closed to LAN lines and it costs less to use a wired LAN connection for them. Also, each intersection with high accident rate has a dedicated RSU assigned to it since they are too far apart to share one RSU.

Next, we use 20 realizations for each of the 3 kinds of traffic density to evaluate the performance of the RSU infrastructure resulting from the optimization. Fig. 2 presents the resulting coverage performance of the vehicular network for different traffic conditions, with the desired coverage shown in the last value of each curve at the x-axis.

As shown in Fig. 2, the RSUs are always able to achieve 98.6% coverage in peak traffic hours, but they could only coverage all the streets with probability of 0.9. During normal traffic hours, it is shown in Fig. 2 that the coverage capability of the proposed roadside infrastructure can satisfy the coverage requirement of 93.6% with probability of 1. Although the coverage requirement during night is 5% lower than normal traffic hours, only in 93.3% of the realizations can the RSUs fulfill the requirement (Fig. 2). The reason for these variations

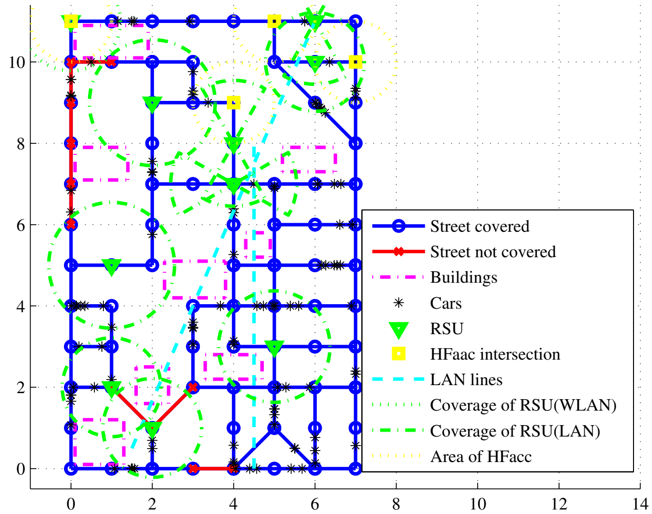

Fig. 1. Optimized deployment of roadside infrastructure with randomly generated traffic

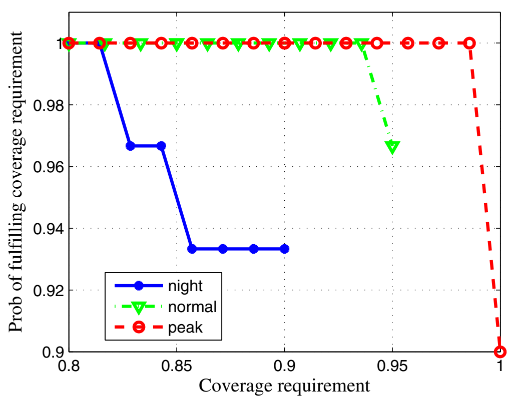

Fig. 2. Probability of Fulfilling Coverage Requirement under 3 Traffic Conditions

is that higher vehicle density could contribute to more IVCs and thus extend the coverage of RSU.

B. Key parameters analysis

An interesting outcome of our results is the trade-off between the cost and the coverage requirement. When we impose a higher coverage requirement on the design of roadside infrastructure, the associated cost will increase. To study this trade-off, we vary the coverage requirement corresponding to three traffic conditions from 0.2, 0.15, and 0.1 to 1, 0.95 and 0.9 respectively. For visual clarity, only the coverage requirement for peak hours is shown as x-axis in Fig. 3. The coverage requirement for normal traffic hours and night hours are 0.05 and 0.1 lower than that of peak hours respectively. As shown in Fig. 3, the number of RSU and cost associated both increase with the increase in the coverage requirements. It is also interesting to note that the cost for roadside infrastructure in Fig. 3 might increase while the number of RSUs installed remains the same. This result demonstrates that the cost of individual RSUs depends both on the transmission power and the network solutions at the location. While keeping the total number of RSUs fixed, the cost may increase due to change of location or transmission power level.

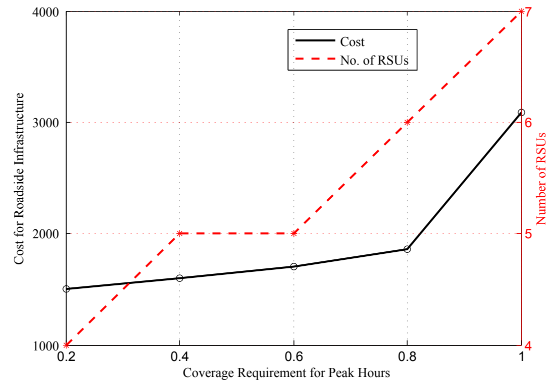

Fig. 3. Coverage Requirement versus Number of RSUs and Cost for Roadside Infrastructure

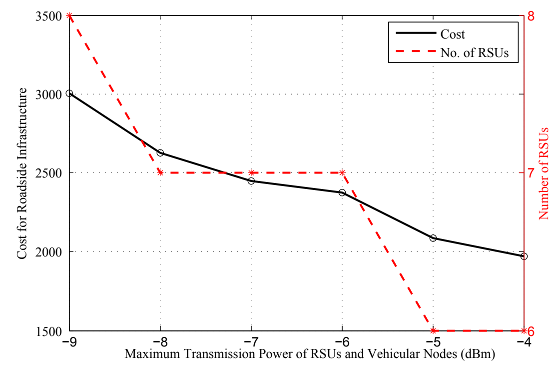

Fig. 4. Transmission Power of Vehicular Nodes versus Number of RSUs and Cost and Number of RSUs

In the next experiment, there are three transmission power levels available for roadside infrastructure, having a -2dBm and -4dBm decrease from the maximum transmission power shown as the x-axis of Fig. 4. Meanwhile, the transmission power of the vehicular nodes is the same as the maximum transmission power of the RSUs'. Fig. 4 shows that as the maximum transmission power increases, both the number of RSUs and cost decrease. The reason for the improved performance is two fold. First, as the coverage range of the individual vehicle increases, more communications can be performed between vehicles, as a result of which they share the burden of coverage with roadside infrastructure. Second, the coverage capability of individual RSU may increase, and thus we need less RSUs to fulfill the same coverage requirement.

Similarly, if we increase the maximum number of hops between vehicles, the number of RSUs and the cost for the roadside infrastructure will decrease, as shown in Fig. 5. However, depending on the actual routing scheme, the transmission delay increases with higher number of hops in the routing of IVC. Therefore, there is also a trade-off between transmission delay and the cost for roadside infrastructure, which is illustrated in Fig. 5.

It is worth noting that the increase of both cost and number of RSUs are non-linear in Fig. 3 and Fig. 5. For instance, in Fig. 3 as the coverage requirement increases from 0.2 to 0.8, the cost only increases by 23.6%. However, the cost goes up by 66.3% when the coverage requirement increase from 0.8 to 1.

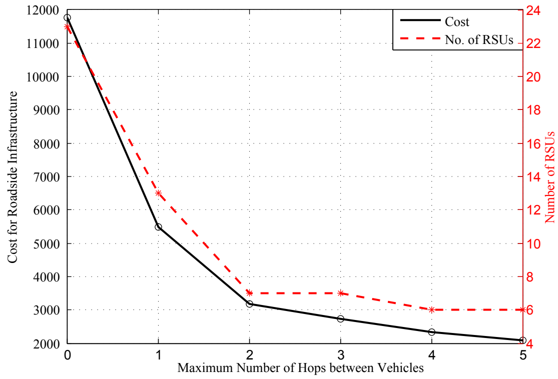

Fig. 5. Maximum Number of Hops versus Number of RSUs and Cost and Number of RSUs

TABLE I
SCALABILITY OF THE OPTIMIZATION ALGORITHM

Number of realizations	Normalized size of map	Number of RSUs	Achievable coverage	Runtime
5	5×5	4	89%	0.8972
10	5×5	6	93%	2.9193
5	10×10	15	95%	10.4857
10	10×10	12	95%	30.7461
5	20×20	39	93%	93.3897
10	20×20	39	95%	784.2071

The non-linearity also exists when we vary the maximum number of hops allowed, as shown in Fig. 5. The cost drop becomes insignificant with larger maximum number of hops between vehicles. The reason is that the probability of having more than 2 multi-hops is very low due to the density of vehicles assumed in the model. Therefore, limitation of maximum 3 or more hops imposes a very loose constraint on the system. Due to the non-linearity of the cost, Fig. 3 and Fig. 5 are very useful references when the network is designed.

C. Scalability of the optimization algorithm

A vehicular network may be as small as a neighborhood with only a few blocks, or as large as an entire city. Therefore, scalability of the solutions is a very important aspect of the optimization problem formulation. In addition to the size of the map, the number of realizations $|R|$ also affects the runtime of the optimization. Although small number of realization give results quickly, the randomness of the traffic may degrade the performance of the resulting RSU deployment. Next, we vary both the number of realizations and the size of map. The system performance and optimization runtime are analyzed to evaluate the scalability of the algorithm.

Table I reflects the scalability of the optimization scheme. The number of realizations for optimization is shown in the table, and the number of realizations for evaluation is set to be 20 with normal traffic. Other simulation settings are the same as RSU coverage capability evaluation. In addition, the achievable coverage is the RSU coverage that the roadside infrastructure could achieve with a probability of 1 under normal traffic conditions.

As shown in Table I, the runtime increases both with the increase in the number of realizations and the size of the area under consideration. Since the placement and configuration of the roadside infrastructure would not be changed frequently, the runtime for optimization of the network is reasonable. For instance, consider the last two rows of the Table. It only takes about 1.5 minutes to obtain the optimal deployment for an area of $16km^2$, which is about the size of Cambridge, Massachusetts, and the RSU coverage can be at least 93%. A high RSU coverage can be achieved with more realizations, as shown in the last row of Table I.

In summary, in this work, we propose an optimization scheme for RSUs allocation and configuration in vehicular communication systems. Future work, should consider more advanced communication protocols between the nodes and also incorporate additional performance constraints such as delay and power considerations.

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