Joint Gateway and Relay Roadside Unit Placement in Vehicular Networks

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1. Introduction

Roadside units (RSUs) collect and disseminate traffic and environmental data from/to vehicles in vehicular networks. They also can support diverse applications, services, and even on-road Internet access. Vehicular network performance largely depends on the RSU density and their placement, and the carefully deployed RSUs can provide more reliable infra connectivity. Thus RSU placement study is a critical research issue in vehicular networks. In the early stage, the market penetration rate of on-board units (OBUs) will be low, and the connectivity between vehicles will not be ensured. Thus the RSUs' coverage should be as large as possible to provide better connectivity for vehicles. Therefore, it is highly desirable to provide as large coverage as possible in a cost effective manner by using different types of RSUs.

Many RSU placement schemes have been proposed to improve infrastructure connectivity, and they leverage one RSU type to maximize contact opportunity [1] or to minimize the total cost under desired connectivity, coverage requirements, or service area coverage [2] - [4]. On the other hand, a few studies have been conducted on the placement exploiting different types of RSUs [5], [6]. The placement schemes in [6] determine the positions of gateway RSUs (GRSUs) but assume that relay RSUs (RRSUs) cover the target area in advance.

We investigate the joint RSU placement problem to deliver the cost effective infrastructure connectivity for the vehicles. GRSUs are connected to backhaul to serve Internet access or other access services, while RRSUs should be connected to GRSUs directly or through the other RRSUs. On the other hand, a GRSU requires higher placement cost compared to a RRSU [6], and this cost-connectivity trade-off can be useful in RSU placement study.

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Thus we propose a three-stage placement scheme to select the position sets of GRSUs and RRSUs, and our goal is to maximize the network performance under the budget and coverage constraints. For the initial GRSU placement, we define the virtual transmission range that is an extended transmission range of a GRSU with the range of a RRSU. RRSU positions are chosen by a branch and bound method with the minimum cost increase. Lastly the RRSU positions are replaced by GRSUs to maximize the network utility in a greedy manner. The simulation tests evaluate our proposed placement scheme and the different approaches for the virtual transmission ranges.

2. RSU Coverage Model

In this section, we describe our proposed RSU coverage model. Consider a simple road topology shown in Fig. 1, where each road consists of *segments* made up of a part of the road from an intersection to its neighboring intersection. In our system, RSUs are placed to cover the road topology. However, in general, feasible *positions* for the RSUs to be placed are constrained by legal and geometric restrictions, and various structures such as traffic lights, traffic signs, streetlights, and telephone poles. Thus, we assume that the feasible positions are chosen in priori and the number of the positions is finite.

Now we can define a set of the feasible RSU positions, denoted by $X=\{x_1,\ldots,x_n\}$. In case of different candidate position sets for GRSU and RRSU, we use two subsets of X, namely X^G and X^R, for GRSUs and RRSUs respectively, where $X^G \bigcup X^R = X$. Note that X^G and X^R need not to be a partition of X, *i.e.*, $X^G \bigcap X^R$ is not necessarily an empty set. In addition, we assume that every GSRU has the same transmission range TX^G, every RRSU has the same transmission range TX^R, and $TX^G > TX^R$.

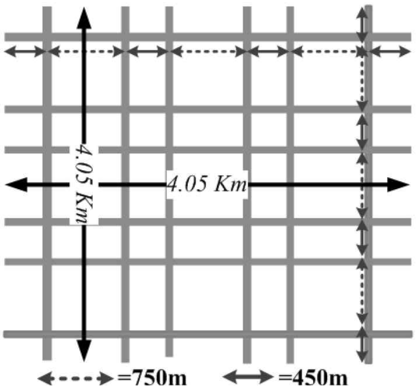


Figure 1. A Road Topology

On the other hand, consider a segment in the road topology as shown in Fig. 2. Without loss of generality, we assume that two ends of the segment are feasible RSU positions x_i and $x_{i+1} \in X$. In this case, the segment can be split into several *subsegments* based on possible combinations of RSU placement at x_i and x_{i+1}.

As illustrated in Fig. 2, suppose that $x_i \in X^G \bigcap X^R$ and $x_{i+1} \in X^G - X^R$. That is, either a GRSU or a RRSU can be placed at x_i, and only a GRSU can be placed at x_{i+1}. In this example, a segment can be split into four subsegments s_j, s_{j+1}, s_{j+2}, and $\check{s}$ based on cov-

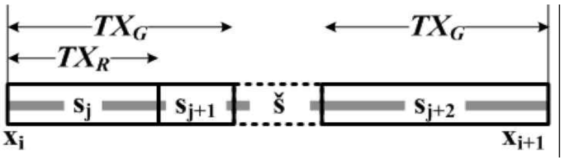


Figure 2. Subsegments of A Segment

erage of possible RSU placement combinations, which is specified by their transmission ranges. Specifically, s_j is a subsegment covered by an RSU if either a GRSU or a RRSU is placed at x_i, s_{j+1} is a subsegment covered only if a GRSU is placed at x_i, s_{j+2} is a subsegment covered if a GRSU is placed at x_{i+1}, and $\check{s}$ is a subsegment covered by no RSU at x_i and x_{i+1} (if it exists). Note that $\check{s}$ is ignorable since it has no use in RSU placement.

To this end, we split all segments in the road topology into subsegments and remove subsegments covered by no RSU for simplicity. Denote the set of remaining subsegments in the topology as $S=\{s_1,...,s_m\}$. Based on S and X^G such that $|X^G|=n^G$, we define a *coverage matrix for GRSUs* as a $m\times n^G$ matrix $\mathbf{A}^G=[a^G_{ij}]$ where its element a^G_{ij} is 1 if a GRSU placed at x_i covers subsegment s_j, otherwise 0. Similarily, based on S and X^R such that $|X^R|=n^R$, we define a *coverage matrix for RRSUs* as a $m\times n^R$ matrix $\mathbf{A}^R=[a^R_{ij}]$ where its element a^R_{ij} is 1 if a RRSU placed at x_i covers subsegment s_j, otherwise 0.

We also define coverage matrices for GRSUs and RRSUs, denoted by $\mathbf{A}^G=[a^G_{ij}]$ and $\mathbf{A}^R=[a^R_{ij}]$, respectively.

3. Problem Statement

In this section, we formulate a joint GRSU-RRSU placement problem in the RSU coverage model. At first, we denote placement vectors for GRSU and RRSU by Π^G and Π^R respectively. Π^G is a $1\times n^G$ matrix which indicates whether a GRSU is placed at $x_i\in X^G$, and Π^R is a $1\times n^R$ matrix which indicates whether a RRSU is placed at $x_i\in X^R$. An element of the matrices is set to 1 if corresponding type of a RSU is placed at x_i, otherwise 0.

Our joint GRSU-RRSU placement problem is aimed to maximize total utility of 'covered' segments in the road topology over the variables Π^G and Π^R:

$$\begin{array}{ll} \underset{\Pi^G,\Pi^R}{\text{maximize}} & \sum_{s\in S} U_s(\Pi^G,\Pi^R) \\ \text{subject to} & \mathbf{A}^G\Pi^G+\mathbf{A}^R\Pi^R \geq \mathbf{1}_{|S|}, \\ & c^G\cdot\mathbf{1}^{T}_{n^G}\Pi^G+c^R\cdot\mathbf{1}^{T}_{n^R}\Pi^R \leq B, \\ & X(\Pi^G)\bigcap X(\Pi^R)=\varnothing, \\ & \Pi^G\in\{0,1\}^{1\times n^G}, \\ & \Pi^R\in\{0,1\}^{1\times n^R}, \end{array}$$

where $U_s(\cdot)$ is a utility function for subsegment s discussed later, $\cdot^{T}$ is the transpose operator, c^G is cost to place a GRSU, c^R is cost to place a RRSU, $\mathbf{1}_z$ is a $1\times z$ column vector of ones, B is a fixed budget, $X(\Pi^G)$ is set of GRSUs selected by Π^G, and $X(\Pi^R)$ is set of RRSUs selected by Π^R. Note that '$\geq$' of the first constraint is the element-wise inequality.

In the optimization problem, the first constraint requires that each subsegment must be covered by one or more RSUs, which represents covering constraint. This strict requirement may not satisfy with the second constraint which represents budget constraint of this problem. Thus, we implicitly assume that the feasible region of this problem is nonempty. The third constraint requires that at most one RSU can be placed at each position $x_i \in X$.

Now we discuss the utility function of subsegment s, namely $U_s(\Pi^G, \Pi^R)$ in terms of Π^G and Π^R. Given Π^G and Π^R, subsegment s is covered by one or more RSUs by the RSU coverage model. If a GRSU covers s directly, the GRSU can serve the Internet with its maximum bandwidth. On the other hand, if a RRSU connected to a GRSU via a path (consisting of the two ends and intermediate RRSUs) covers s directly, the GRSU can serve the Internet with its effective bandwidth (*i.e.*, the amount of data transmitted divided by the sum of transmission times for links in the path) Therefore, we have several choices of $U_s(\Pi^G, \Pi^R)$ as a function of the (maximum or effective) bandwidths. Among them, we choose $U_s(\Pi^G, \Pi^R)$ as the maximum of the bandwidths each of which is divided by the number of its hop distance. This penalizing factor is appropriate to balance the maximum hop distance of connected RSUs for the installed GRSUs.

4. A RSU Placement Scheme

Although we formulate a combinatorial optimization problem for joint GRSU-RRSU placement in the road topology, there is no known algorithm to solve the problem except exhaustive search. In addition, it is not plausible to apply the exhaustive search when n^G and n^R are sufficiently large. To this end, we design a placement scheme based on the following considerations. 1) Under the full coverage constraint, more GRSUs should be placement with a given budget to serve better performance with shorter hop distances to backhaul connectivity. 2) The number of connected RSUs to GRSUs should be balanced for the max-min fairness of network utility of vehicles at all subsegments. Based on the considerations, we propose a three-stage RSU placement scheme including ‘initial GRSU placement’, ‘temporary RRSU placement’, and ‘RSU replacement’.

Stage 1 (Initial GRSU placement): This stage determines the initial GRSU position set as the criterion of the following stages. In this paper, we focus on the budget sizes smaller than the minimum one ensuring the fully covered network only by GRSUs. Thus we exploit the extended transmission ranges (called *virtual TXs*, denoted by TX^v) to select the position set of GRSUs. We define TX^v as follows so that the length of uncovered subsegments is close to an integer multiple of TX^R for the cost effective RRSU placement in the next stage.

Definition 1 (Virtual transmission range):

$TX_k^v = TX^G + \frac{k}{2} \cdot TX^R$, where $0 \leq k \leq K$.

We find the position sets of GRUSs satisfying the budget constraint by solving set covering problems with the virtual TXs. CPLEX or GLPK (GNU Linear Programming Kit) can be applied for the set covering problems to minimize the number of required GRSUs. The maximum value of K of TX^v depends on the given topology. For example, we need at least 6 GRSUs at this stage for the topology in Fig. 1. In other words, we can find K of the above definition when the required number of GRSUs is converged. At the end of this stage, the virtual TXs with B's are not considered in the following stages, where $B' > B$.

Stage 2 (Temporary RRSU placement): This stage places RRSUs for the uncovered areas from Stage 1, and these areas are defined as follows.

Definition 2 (Section): A section is defined as the subsegment set between a neighboring selected GRSU pair. When a GRSU has not a neighboring one for a given direction, a section is the subsegment set to its adjacent boundary of the direction.

The number of candidate positions of RRSUs in each section largely depends on the extended transmission ranges. Note that longer TX^v makes a larger candidate position set for a section, but the number of sections decreases for the target area. This stage selects the minimum number of RRSU positions to fully cover all subsegments, and all the RRSUs at the positions should be connected to at least one GRSU directly or through the other RRSUs. Based on the constraints with regard to the coverage and the backhaul connectivity, we determine the RRSU positions for each section in a greedy manner.

In Section 5, we consider a uniform subsegment size based on a unit distance, and this stage uses the minimum number of RRSUs to cover the given section for the utility cost efficiency. As mentioned above, there are two cases of sections whether a GRSU has its neighboring one. Thus the required number of RRSUs for each section is as follows for our simulation:

(1) $\left\lceil \frac{D_{Section} - 2TX^R}{TX^R} \right\rceil$ for the section between a neighboring GRSU pair, and

(2) $\left\lceil \frac{D_{Section} - TX^R}{2TX^R} \right\rceil$ for the section between a GRSU and its adjacent network boundary.

$D_{Section}$ denotes the distance of a section. Because we assume that $TX^G \geq TX^R$, $D_{Section} - 2TX^R$ and $D_{Section} - TX^R$ are the lengths that should be covered by RRSUs, instead of $D_{Section} - 2TX^G$ and $D_{Section} - TX^G$ respectively. We apply a branch and bound method for each section to select RRSU positions, and we do not need to consider the positions that cannot ensure the fully covered section with the minimum RRSUs. The objective is to maximize the network utility. After that, we calculate required cost and network utility for each TX_k^v.

Stage 3 (RSU replacement): Lastly, this stage leverages the placement results from Stage 2 and replaces the selected RRSUs with additional GRSUs in a greedy manner. We select candidate positions of GRSU iteratively from the GRSU position set excepting the selected ones at Stage 1. After that, we exclude the RRSUs that their coverage is involved in the selected GRSUs. At the beginning of this stage, total placement cost can decrease based on the RSU placement costs and the number of replaced RRSUs by an additional GRSU, and we show it in the following section.

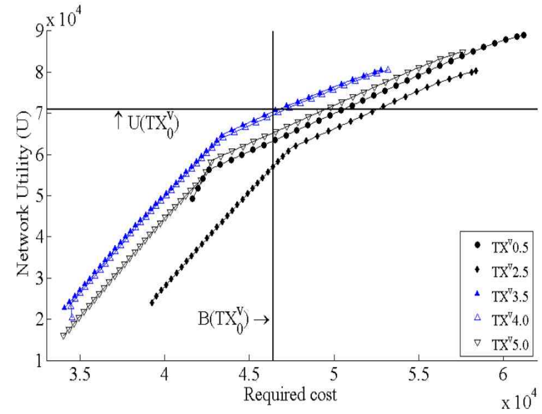
Each GRSU position is chosen under the utility-cost efficiency to maximally improve the network utility over the increased budget size. The nearby RRSUs in adjacent sections to the added GRSU are controlled to improve the network utility. Hop counts to nearby GRSUs can be balanced through the RRSU position modification. This replacement is repeated until the required cost approaches the given budget size. We terminate this stage when there is not RRSU in Section 5.

5. Simulation Results

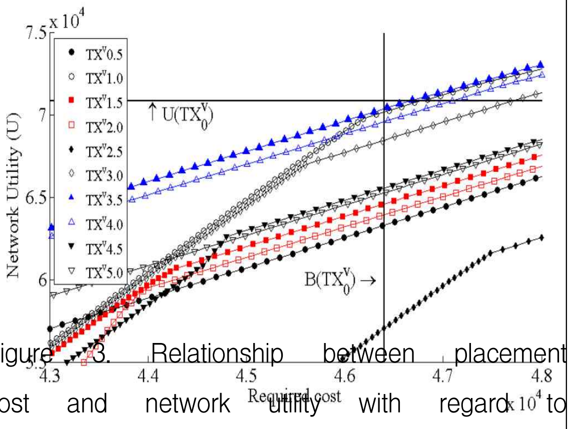
Fig. 1 illustrates the road topology for the simulation tests, including two segment lengths, 450m and 750m. We set the length of a subsegment to 10m. We assume that RSUs can be placed at the boundaries between neighboring subsegments and the candidate position sets of GRSU and RRSU are same, $X = X^G = X^R$. Thus the topology consists of 4,860 subsegments and 4,836 candidate positions, and the length of whole road is 48.6 Km. K is set to 10. The transmission range is 100m for both RSU types. Two placement cost sets are used, (200, 70) and (200, 30), for (GRSU, RRSU). We solve the proposed placement scheme by utilizing GLPK and C++ programming language on a PC with 3.0GHz CPU and 8.0 GB RAM. We apply the data rates of IEEE 802.11p with 10 MHz channel in 5GHz bands.

When placing only GRSUs, 232 units are required to cover the road topology, and the required budget size and the achievable network utility are 46,400 and 70,878.4 respectively. Both the budget size and the network utility are shown in the following graphs as $U(TX_0^v)$ and $B(TX_0^v)$ respectively, and we consider the budget size as the upper bound of the RSU placement in this paper. With changing virtual transmission ranges from TX_0^v to TX_5^v, the number of GRSUs is decreased from 232 to 28, and the network utility is reduced from 70,878.4 to 16008.9. The required costs also decreases from 46,400 to 34,020 with placement cost set of (200, 70) and 17,780 with that of (200, 30). The utility and budget pairs for TX^vs are used for the last stage and described as the initial points of the graphs.

Fig. 3 shows the relationship between the required placement cost and the network utility



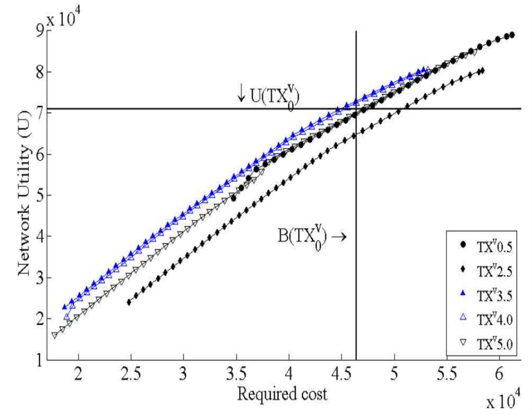
(a) Selected TX^v in whole cost range



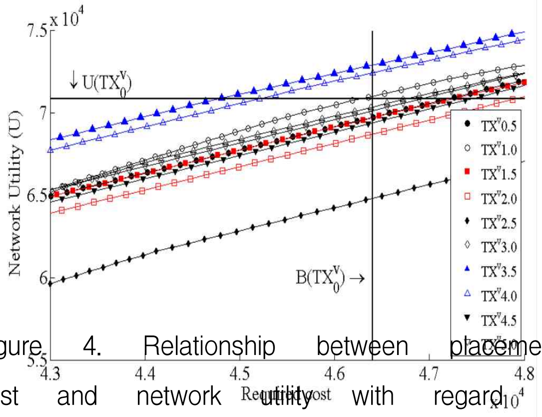
(b) Selected cost range

Figure 3. Relationship between placement cost and network utility with regard to virtual transmission ranges: Placement cost (GRSU = 200, RRSU = 70)

of the virtual transmission ranges for Stage 3 with placement cost set (200, 70). In this figure, we include the selected TX^vs and the selected cost range for better readability. With the budget size ranging from 34,080 and $B(TX^v_0)$, $TX^v_{3.5}$ shows the best performance in terms of the network utility, and it reaches to budget size 52,800 with 264 GRSUs at Stage 3 as illustrated in Fig. 3(a). $TX^v_{5.0}$ only has the placement results with the budget size between 34,020 to 34,080. $TX^v_{2.5}$ provides the lowest cost-utility efficiency. The graphs excluded from Fig. 3(a) are located between $TX^v_{2.5}$ and $TX^v_{3.5}$.



(a) Selected TX^v in whole cost range



(b) Selected cost range

Figure 4. Relationship between placement cost and network utility with regard to virtual transmission ranges: Placement cost (GRSU = 200, RRSU = 30)

In Fig. 3 and 4, decreasing slop of the graphs is caused by the number of RRSU positions replaced by each additional GRSU. The change of slope of the graphs in Fig. 3(a) occurs more drastically than that in Fig. 4(a) due to the higher placement cost of RRSU. Fig. 4(b) illustrates that exploiting different RSU types can provide better performance than using only GRSUs in terms of the network utility. $TX^v_{3.5}$, $TX^v_{4.0}$, and $TX^v_{1.0}$ have higher utilities with the budget sizes equal or lower than $B(TX^v_0)$.

We do not use smaller transmission range extension than $k/2$ for the virtual transmission

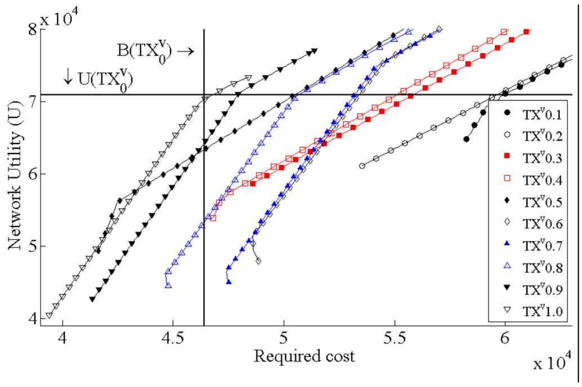


Figure 5. Relationship between placement cost and network utility: Different extension units with placment cost (GRSU = 200, RRSU = 70)

range due to the low utility cost efficiency. In Fig. 5, the test results with different extension factor $k/10$, and $TX^v_{0.5}$ and $TX^v_{1.0}$ are only used for the proposed RSU placement. Except these two TX^vs, the others do not have any highest utility points, and only $TX^v_{0.9}$ and $TX^v_{0.8}$ are appeared, under the budget sizes lower than $B(TX^v_0)$. The reason is that the uncovered areas between neighboring GRSUs are close to the integer multiples of TX^R. From the result, we can also infer that the placement results of GLPK have small overlapped coverage.

6. Conclusion

In this paper, we investigate the joint RSU placement problem considering the connectivity of RRSUs to GRSUs and the full coverage constraint. The goal of our placement study is to maximize the network utility with a given budget. To this end, we propose a three-stage RSU placement scheme with the virtual transmission ranges. Simulation tests evaluate the proposed scheme with the different placement cost sets and the different extension approaches of the virtual transmission ranges.

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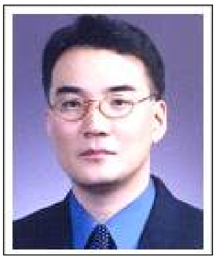

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