Smart Infrastructure Design for Smart Cities

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In intelligent transportation systems, roadside unit (RSU) deployment should be well designed because RSUs act as service providers and gateways to the Internet. The authors' RSU deployment strategy maximizes the communication coverage and reduces the energy consumption of RSUs.

ICT makes cities "smart," capable of managing infrastructures more effectively and efficiently. In the smart grid, for instance, ICT is applied to a traditional electric grid to more efficiently use electricity. Intelligent transportation systems (ITS) are a more familiar example because most of us have benefited from ITS technologies, including car navigation and electronic toll collection.

With advances in automotive and wireless technologies, vehicular ad hoc networks (VANETs) have emerged to help ITS provision a wide spectrum of safety and information applications to drivers and passengers. VANETs can also collect large amounts of data from distributed vehicles to meet several objectives, such as traffic control, safety assistance, and environmental monitoring.[1] Generally, communication in VANETs can be classified into two types: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), as Figure 1 shows. In V2V communication, vehicles equipped with on-board units communicate with each other through wireless channels. V2V communication testing

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has already begun with industry and worldwide automakers—for example, Toyota,[2] Honda,[3] Volvo,[4] and BMW[5] have all developed their own testbed systems. In academia, cooperative downloading and message dissemination using V2V communication have been studied to improve delivery efficiency.[6] Some research efforts have been made to solve security and privacy problems because data transmission through V2V communication can expose vehicular users' personal information to malicious actors.[7]

Meanwhile, in V2I communication, vehicles connect to the Internet through one of two ways: cellular networks or—more typically, due to their much lower communication costs—roadside units (RSUs). In Japan, more than 1,000 RSUs have been deployed, mainly around highways. RSUs provide information services, currently focused on safety-related information, for on-road vehicles using the 5.9-GHz dedicated short range communications (DSRC) spectrum. However, more options are likely to be offered in the near future—for example, for entertainment purposes. The US has allocated a large budget for next-generation ITS. For instance, New York City will receive 42 million dollars to upgrade ITS such as traffic signals with V2I technology.[8]

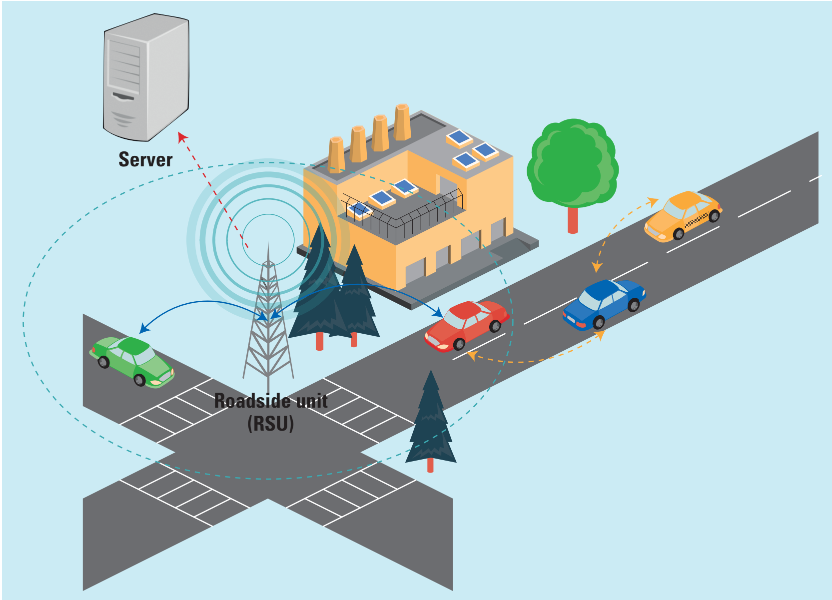

Figure 1. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. In the former, vehicles equipped with on-board units communicate with each other wirelessly. In the latter, vehicles connect to the Internet through cellular networks or roadside units (RSUs).

Intuitively, the more RSUs there are deployed anywhere in smart cities, the more people's quality of life (QoL) improves. However, RSU deployment can fail not only because initial setup costs are too expensive, but also because less frequently used RSUs can waste energy. Energy efficiency cannot be neglected—it is a primary mission of smart cities.[9,10] On the other hand, if the number of RSUs is decreased to save on setup costs and energy consumption, service availability and connectivity could get worse because of limited RSU communication coverage. Thus, a tradeoff exists between energy consumption and communication coverage.

Here, we investigate this RSU deployment problem and formulate it as an optimization problem with multiple objectives. We then find a solution using an evolutionary algorithm and show through extensive simulations that our solution maintains high energy efficiency while guaranteeing communication coverage.

Advantages of VANETs

With the recent penetration of Long-Term Evolution, Wimax, and 3G networks, users can enjoy online shopping, check email, and watch videos even while driving a vehicle. However, VANETs remain necessary to assist with Internet access in motion for the following reasons. First, cellular network capacity can reach near-limits because of heavy traffic coming from cellular networks.[11] It is thus costly for most people worldwide to access the Internet via cellular networks—an average of US$60 per 7 Gbytes in Japan (www.nttdocomo.co.jp) and US$10 per 1 Gbyte in Canada (www.fido.ca). Second, using a monitor embedded in a vehicle is safer and more convenient than using a small mobile phone screen when users in motion access the Internet, especially for entertainment purposes. Lastly, mobile phones are battery powered; frequently accessing the Internet via mobile phone uses its energy up quickly, as does video streaming. In addition, it is known that bandwidth fluctuation has a significant impact on a mobile phone's energy consumption.[12] In other words, bad connectivity due to weather, buildings, or other factors consumes much more energy than good connectivity. Although mobile phones can be charged in vehicles, a vehicle's equipped device is obviously easier to use.

RSU Deployment Problem

RSU deployment needs to be well planned for the following reasons. First, the cost for deployment and operation or management is high—for example, US$13,000–$15,000 per unit and $2,400 per unit per year for deployment and operation or management, respectively.[13] Because of each RSU's limited communication range, densely deploying RSUs provides pervasive service throughout a city; however, service providers might have to set expensive access fees for RSUs that could discourage people from using them. Also, once an RSU is deployed, it is not easy to uninstall or move to other places. Thus, it is important to balance communication coverage and the number of RSUs. In our previous work, we maximized communication coverage with a given number of RSUs.[14] It is useful for service providers to plan RSU deployment on a limited budget.

The next issue is then the energy efficiency of RSUs. Although RSUs are outlet-plugged, energy waste cannot be ignored given our increasing awareness of environmental issues. Huge amounts of energy can be wasted because vehicle traffic density varies temporally as well as spatially. For example, numerous vehicles pass through an RSU deployed in the center of an urban city during daylight; however, almost no vehicles pass through the RSU at midnight. This energy waste can be avoided by turning RSUs on or off as the situation demands. This should be well studied; otherwise, network connectivity can seriously degrade. Thus, we study how to minimize an RSU's total energy consumption while maximizing overall network connectivity.

The RSU deployment problem has been studied elsewhere.[15–17] One study aims at minimizing the costs of RSU deployment with the constraint that all service areas should be covered.[15] The solution is a branch and bound method, which shows that the probability of uncovered areas increases as the average number of required RSUs decreases. In another study, the authors propose a new mathematical linear programming formulation to solve the RSU deployment problem.[16] Total network cost and the connectivity maintenance between sensors and RSUs are considered in the deployment. The proposed method is effective for solving medium-sized problems. In another work, a genetic algorithm is proposed for solving the maximum coverage with time threshold problem (MCTTP).[17] However, none of these works deal with the energy consumption and communication connectivity of VANETs.

On the other hand, several researchers consider RSU energy efficiency.[18,19] One analytic model with linear time complexity was developed for the optimal number of active RSUs under a connectivity constraint.[18] In another study, the authors aimed at finding the optimal sleep schedule of an RSU in a given time period to minimize its overall energy consumption while maintaining network connectivity. However, these studies do not consider communication coverage in VANETs. We summarize these related works in Table 1.

In this article, we consider the RSU deployment problem as a multiobjective optimization problem in which communication coverage is considered a constraint, and minimizing RSUs' total energy consumption and maintaining communication connectivity are considered two objectives. We use an evolutionary algorithm (EA) to find a solution for this multiobjective optimization problem, which is more efficient than traditional approaches.

RSU Deployment Optimization

Figure 2 shows a model of optimal RSU deployment: (x_i, y_i) denotes the 2D position of RSU i, and binary variable s_i denotes whether RSU i is in active mode or sleep mode. We assume that vehicles are randomly distributed in a target area, and each vehicle communicates with an RSU when it moves into that RSU's communication coverage. On a road with many vehicles, RSUs always need to be activated for communication with these vehicles to ensure communication connectivity. When the vehicle traffic density decreases, some RSUs can be turned to sleep mode to lower energy consumption, which could result in them losing communication connectivity. Thus, we consider the communication coverage as a constraint and minimizing total energy consumption and maximizing communication connectivity as two objectives:

- *Communication coverage.* We assume that the city is divided into $X \times Y$ grids. When a grid is within the communication coverage of at least one RSU, it is regarded as a *communication area*. The total communication area is the sum of these grids. Service providers usually require that a VANET cover certain areas—this is a *communication coverage requirement*.
- *Total energy consumption.* The total energy consumption is the energy consumed by all RSUs deployed in the city. The energy consumption of each RSU depends on its status: active or asleep. Here, we consider only these two statuses; an active RSU consumes much more energy than one that is asleep.
- *Communication connectivity.* We compute communication connectivity from VANETs' throughput performance. This communication connectivity can be measured as P_{R_i}/P^v, where P_{R_i} is the number of data packages that RSU i successfully received from each vehicle; $i = 1, ..., N_R$; and P^v is the total number of packages generated by all vehicles in the city. For simplicity, we assume that data transmission succeeds whenever a vehicle is within the communication coverage of an active RSU.

To satisfy the communication coverage requirements, we seek an optimal RSU deployment to minimize the total energy consumption of RSUs and maximize communication connectivity. Finding optimal RSU deployment—that is, a combination of RSU positioning and status—is an NP-complete problem. In addition, the more RSUs there are in a big city, the greater the search space. For example, consider 150 RSUs deployed in a city. Each RSU's communication coverage is set as 250 m. These 150 RSUs will be placed in a 5×5 km^2 area in the city. Assume that the target area is divided into 50×50 grids, and more than one RSU can be placed on a grid. Thus, the number of search combinations is $2 \times 150 \times (50 \times 50)^{150} = 300 \times 2{,}500^{150}$.

Thus, we use the EA to find solutions for the RSU deployment problem; Figure 3 shows how the EA works. In this algorithm, we define the population, which consists of M individuals.

Table 1. Related work in roadside unit deployment.

Proposed approach	Communication coverage	Energy efficiency
Po-Chiang Lin[15]	X	
Maher Rebai and colleagues[16]	X	
Evellyn S. Cavalcante and colleagues[17]	X	
Teerawat Kumrai and colleagues[14]	X	
Sok-Ian Sou[18]		X
Feng Zou and colleagues[19]		X
Ours	X	X

Each individual i in the population is represented by multiple segments, which are a set of RSU properties. These properties consist of RSU status s_i and RSU locations x_i and y_i. The number of multiple segments in an individual indicates the number of RSUs n in the target area.

First, the initial population will be generated by random RSU properties. Then, individuals are evaluated using a fitness value that indicates whether the individual is better than others in the population.

Then, the EA selects a pair of individuals who have the highest fitness values as parents. Selected parents reproduce two offspring using a crossover operator with a certain crossover rate. The offspring can mutate with a mutation rate—that is, a probability that random elements of an individual will be flipped into another value; for example, flipped from 0 to 1 or vice versa.

The EA repeats these operators (selection, crossover, and mutation) until the number of offspring achieves size N. Then, this set of offspring is combined with the set of the population. Finally, the EA selects the best M individuals from $M + N$ individuals via the selection operator to be the new population for the next generation. The selection operator is driven based on individuals' fitness values.

This process repeats until the number of generations reaches the maximum decided by service providers. For more details, such as how to

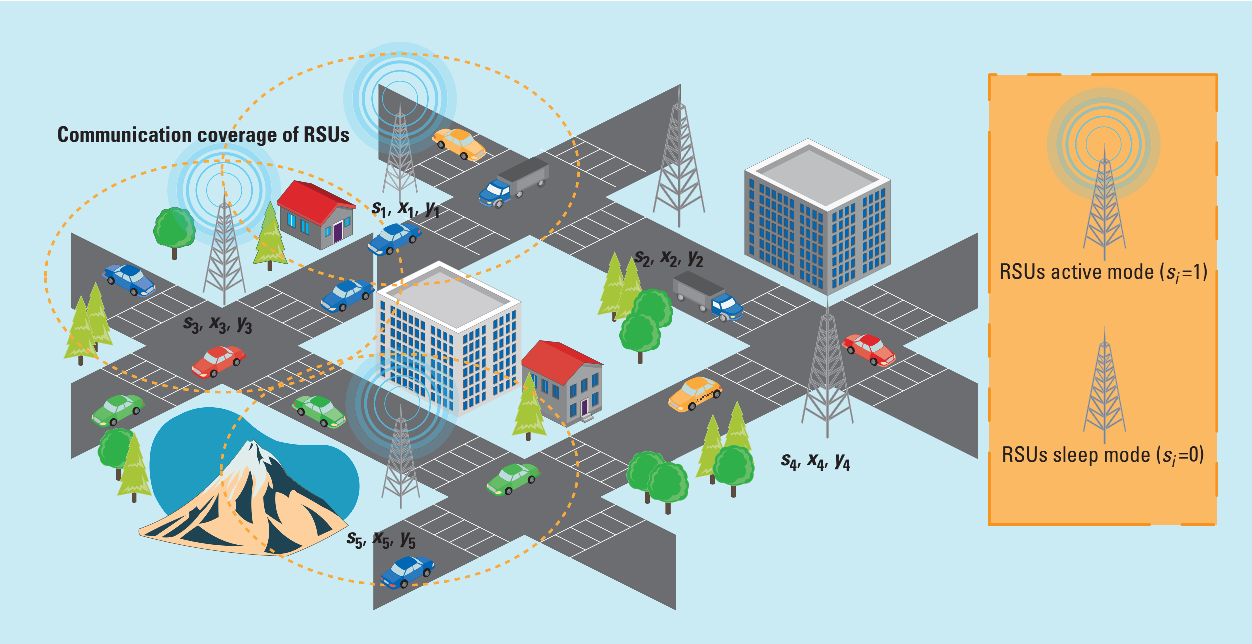

Figure 2. A model of optimal roadside unit (RSU) deployment. Here, (x_i, y_i) denotes the 2D position of RSU *i*, and binary variable s_i denotes whether RSU *i* is in active or sleep mode.

calculate fitness values, readers can refer to our previous work.[14]

Performance Evaluation

In this section, we evaluate the performance of our proposed algorithm for RSU deployment optimization via simulation experiments.

Simulation Setup

We implement a VANET simulator to evaluate our proposed algorithm and simulate a 5 km × 5 km-sized city with a road length of 53 km. We divide this city into 50 × 50 grids with widths of 100 m, which is a common width for some wide urban roads. We assume that, at most, 75 RSUs are deployed in the city, and RSU communication coverage is set to 250 m. The grids covered by RSUs include both full and partially covered ones. The VANET simulator uses broadcasting routing protocols. Vehicles generate sensing data at one packet per second.

Each RSU's energy consumption is derived from the VANET simulator based on the traffic density of roads and corresponding RSU status. We execute the VANET simulator over a period of time and thus calculate the total energy consumption of an RSU in this time period. Each RSU can change its status each second according to the communication coverage requirement.

To execute the EA in these simulations, we use jMetal, a simulator for multiobjective optimization problems with meta heuristics.[20] It is an object-oriented JAVA-based framework. The simulation configurations are set as 100 populations, 2,000 max generations, a 1/*n* mutation rate, and a 0.9 crossover rate.

In the simulations, we evaluate our proposed algorithm's performance in the following two scenarios:

- *Scenario 1*. RSU status is variable (each RSU is either active or sleep).
- *Scenario 2*. RSU status is fixed (all RSUs are active at all times).

Simulation Results

In the simulations, we use the *C*-metric[21] as the performance metric to represent how individuals obtained from one algorithm are better than individuals from another. $C(A, B)$ represents the *C*-metric for algorithm *A* and *B*, which is calculated

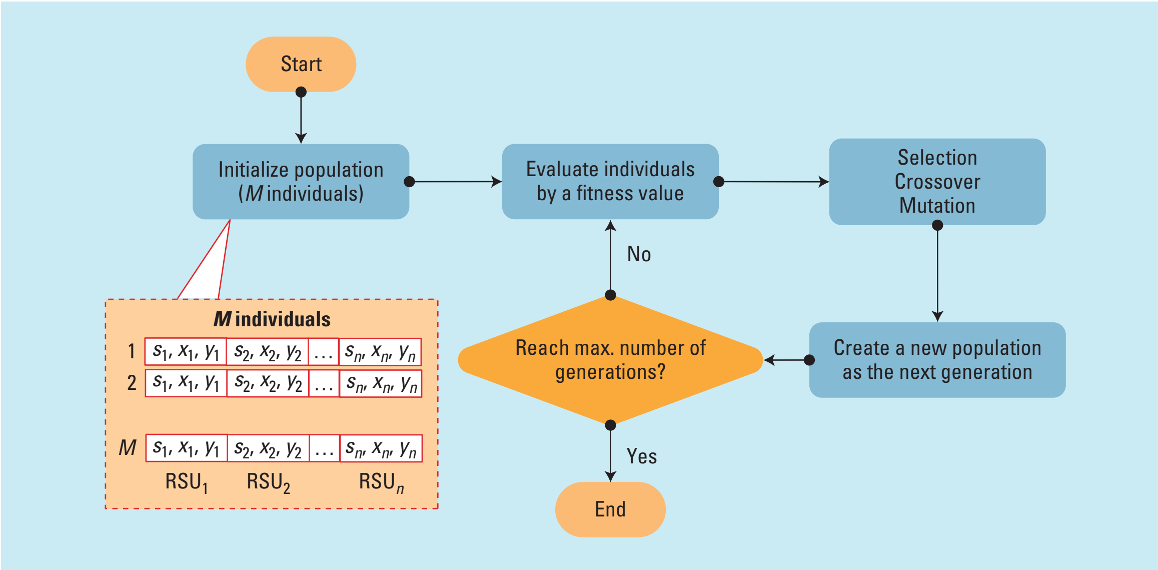

Figure 3. **Process of the evolutionary algorithm. The population consists of *M* individuals, represented by multiple segments.**

by $|\{b \in B | \exists a \in A : a > b\}|/|B|$, where the $>$ operator denotes dominance (for example, $a > b$ means that individual a dominates individual b). If the C-metric $= 0$, no individual in A dominates individuals in B. On the other hand, if the C-metric $=$ 1, at least one individual in A dominates all individuals in B.

Figure 4 shows the results of solutions gained by scenario 1 and scenario 2 in two objectives (energy consumption and data transmission success rate). The results show that the RSUs in scenario 1 consume less energy than those in scenario 2. The average energy consumption decreases by about 7 percent. Moreover, we show the C-metric at generation 2,000. C(*scenario 1*, *scenario 2*) is equal to 0.78. On the other hand, C(*scenario 2*, *scenario 1*) is equal to 0.00. This result demonstrates that scenario 1 is a better nondominated frontier than scenario 2.

Figures 5a and 5b show the performance of the proposed algorithm in two scenarios: communication coverage with communication connectivity and communication coverage with energy consumption. The RSUs in scenario 1 cover fewer target areas while maintaining a higher data transmission rate. Because we consider some RSUs to be sleeping in scenario 1, the communication coverage decreases by about 2 percent. This indicates that communication connectivity is maintained with properly selected RSUs activated.

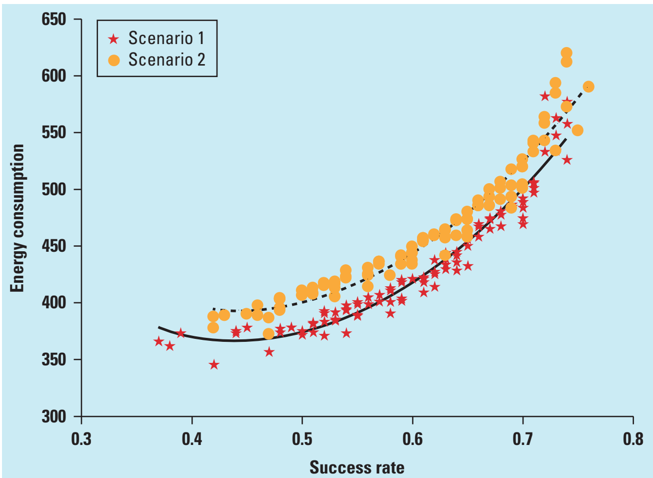

Figure 4. **Performance of the proposed algorithm in energy consumption and success rate. The RSUs in scenario 1 consume less energy than those in scenario 2.**

Our proposed strategy turns inactive RSUs to sleep mode to save energy while achieving stable access for vehicles from active RSUs. Our strategy's performance is verified

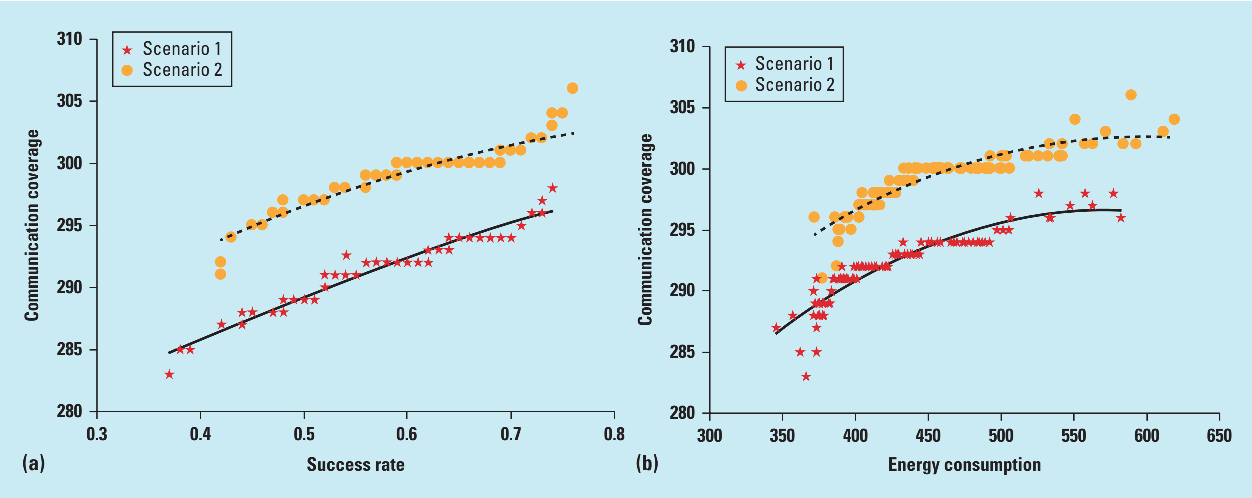

Figure 5. Performance of the proposed algorithm in (a) coverage and connectivity and (b) coverage and energy consumption. The RSUs in scenario 1 cover fewer target areas while maintaining a higher data transmission rate.

through extensive simulations, and experimental results demonstrate that our strategy outperforms a traditional algorithm in terms of both energy efficiency and VANET connectivity. The proposed strategy is helpful in improving people's QoL such that online service is always accessible with a reasonable access fee as they are driving. It also enhances the energy efficiency of smart transportation systems, which might incur additional energy expenditures through VANETs.

In future work, we will further conduct experiments under large-scale and realistic simulation setup environments, such as using real traffic measurements, using a real city map, and varying the communication range of each RSU.

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