Performance-Cost Tradeoff of Using Mobile Roadside Units for V2X Communication

Jeongyoon Heo, Byungjun Kang, Jin Mo Yang, Jeongyeup Paek, *Senior Member, IEEE*, and Saewoong Bahk, *Senior Member, IEEE*

***Abstract*—Roadside unit (RSU) is a communication device for vehicular networks that provides vehicle-to-infrastructure (V2I) connectivity to nearby vehicles. It allows broadcasting of traffic and safety information, Internet connectivity, shared storage, advertisement, as well as supporting and enhancing vehicle-to-vehicle (V2V) communication for future autonomous vehicles. However, high cost of its deployment and management has so far prevented RSUs from being used widely in practice despite its utility and importance. In this paper, we investigate the performance-cost tradeoff and viability of using buses as mobile RSUs (mRSUs). Although there have been some prior works that suggest the use of cars, public transportation, and controlled vehicles as mRSUs to address the cost problem of static RSUs (sRSUs), their assumptions were mostly rather idealistic. We aim to provide a more realistic view of the problem. Through real-world measurements, experiments, analysis, and simulation, we show how mRSUs can replace sRSUs while maintaining the same level of throughput, contact time, and inter-contact time. Our results provide a basis for judging whether it is beneficial to complement sRSUs with mRSUs depending on the deployment environment and cost-performance tradeoff.**

***Index Terms*—Vehicular Network, Roadside Unit (RSU), V2X, V2I, V2V, Mobile RSU, DSRC.**

I. Introduction

As SELF-DRIVING and connected vehicles are emerging as the next generation automobile technologies [1], vehicle-to-everything (V2X) communication, which includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, will play a critical role in future transportation systems. V2X communication can be used to improve safety of drivers and pedestrians, alleviate traffic congestion, and provide useful or entertaining information [2]–[4]. For these reasons, it is expected that the amount of data exchanged through V2X communication will increase tremendously [2].

To handle increased V2X communication traffic and provide connectivity support to vehicles in a scalable manner, Roadside units (RSUs) can be used [5]. RSU is a communication device for vehicular networks, usually deployed as part of an infrastructure along the road side, that provides V2I connectivity to nearby vehicles. It allows broadcasting of traffic and safety information, Internet connectivity, shared storage, advertisement, as well as supporting and enhancing V2V communication. For example, Reis *et al.* [6] show that messages between vehicles can be delivered more rapidly if RSUs connected to each other assist in propagation rather than using V2V communication alone. If in an environment where GPS is inaccurate due to non-line-of-sight (NLoS) or weak signal strength, RSUs can help a vehicle get localized [7]–[10].

In general, V2X connectivity, performance, and its utility improve with larger number of RSUs installed. For example, Qin *et al.* [11] demonstrated that higher density of RSUs results in higher accuracy of localization, and Wang *et al.* [12] showed that average propagation delays increase with inter-RSU distances. Despite its utility and importance, however, high cost of its installation, maintenance, and management has so far prevented RSUs from being widely used in practice. To mitigate this problem, several studies have attempted to optimize RSU deployment to minimize cost while guaranteeing performance requirement [13]–[16].

In this paper, we explore the use of buses as mobile RSUs (mRSUs) and discuss performance features of replacing static RSUs (sRSUs) with bus-based mRSUs. Specifically, through real-world measurements, analysis, simulation, and experiment, we investigate performance-cost trade-offs between mRSUs and sRSUs to show how bus-based mRSUs can replace (and reduce) sRSU while maintaining the same level of network performance. We analyze the *replacement ratio* that provides the same performance with that when using sRSU alone, according to throughput, contact time, and inter-contact time. We also show the results in various degrees of sRSU densities and car speeds. Although there have been some prior works that suggest the use of cars, public transportation, and controlled vehicles as mRSUs (Section II), their assumptions have mostly been rather idealistic and do not consider the trade-off between cost and performance.

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J. Heo, B. Kang, J. M. Yang, and S. Bahk are with the Department of Electrical Engineering, Seoul National University and INMC, Seoul 08826, South Korea (e-mail: jrheo@netlab.snu.ac.kr; bjkang@netlab.snu.ac.kr; jmyang@netlab.snu.ac.kr; sbahk@netlab.snu.ac.kr).

J. Paek is with the School of Computer Science and Engineering, Chung-Ang University, Seoul 06974, South Korea (e-mail: jpaek@cau.ac.kr).

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We aim to provide a more practical scenario and realistic view of the problem.

The contributions of this work are threefold:

- We extend prior work to discuss the characteristics of using buses as mobile RSUs and the effect of substituting a subset of sRSUs with mRSUs.
- We present mathematical analysis as well as simulation studies to investigate the performance-cost trade-offs of using mRSUs in terms of throughput, contact time, and inter-contact time.
- We perform real-world experiments using real dedicated short range communication (DSRC) devices to support our findings and provide practical lessons learned for successful RSU deployment.
- Our findings reveal that more mRSUs may be needed than the reduced sRSUs, and thus the cost of mRSUs needs to be sufficiently lower for the replacement to be beneficial.

We believe our study provides a basis for judging whether it is beneficial to complement sRSUs with mRSUs depending on the deployment environment and the cost differences between mRSUs and existing sRSUs.

The remainder of this manuscript is structured as follows. Section II summarizes related work, and Section III describes two methods of utilizing RSUs that we compare in this work. Then, we analyze the contact time performance of using mRSUs in Section IV. Section VI and Section V evaluate the network performance of mRSUs through real-life experiment and simulations, respectively. Finally, Section VII concludes the paper.

II. Related Work

One approach to minimize the cost of deploying RSUs is to find the optimal locations of static RSUs that achieve the desired performance with least number of devices [13]–[16]. This approach can be combined with the idea of using mobile RSUs, and mRSUs can be complementary to the system with optimal sRSU deployment. However, using only static RSUs makes it difficult to change RSU installation locations and quickly respond to environment dynamics such as changes in traffic volume and road infrastructure. In the event of a malfunction, a visit to the installed location is required for repair which increases management cost.

Another approach for reducing the cost of RSUs is to use alternative devices to act as RSUs instead of using static infrastructure RSUs. For example, Tonguz *et al.* [17] suggested a technique where an ordinary car can act as a temporary RSU. In their proposal, vehicles that travel toward an event (e.g. accident) independently decide to serve as RSUs, and stop briefly (e.g. 30 seconds) to broadcast messages. However, making stops for tens of seconds in the middle of driving and interrupting the flow of traffic seems impractical let alone accounting for the safety, network security, and incentive issues for those drivers.

Unnatural stops can be avoided if they are not moving in the first place. That is, if parked cars can be used as RSUs [6]. Reis *et al.* proposed that, by listening for beacons from nearby vehicles and requesting the coverage maps of neighboring active RSUs, a parked car can build its own coverage map and determine for itself whether to operate as an RSU. However, this is feasible only if the communication module is turned on while the car is parked, possibly resulting in the danger of draining the car battery. We believe no car owner would opt in for that. Also, the density and distribution of parked cars are highly variable and unpredictable, providing challenges for RSU connectivity.

Using personal, un-authorized cars as RSUs can cause security problems. A malicious vehicle owner can attack the system by sending malicious messages, eavesdropping, or dropping messages. Therefore, we need pre-verified, trust-worthy RSUs. To satisfy this requirement, several prior works have suggested using public transportation to assist V2V communication. For example, MI-VANET [18] and BUS-VANET [19] use buses as high-tier nodes that are equipped with better wireless communication devices which provide a longer transmission range than a common vehicle. High-tier nodes constitute the backbone network and are main message deliverer. Low-tier nodes register with high-tier nodes and forward messages through them. However, both of these works are in the context of vehicular ad-hoc networks and does not discuss the RSU deployment problem.

The aforementioned studies using alternative RSUs did not discuss the cost savings achieved by using such devices, nor did they analyze the trade-off relationship between cost and performance. Recently, D. Kim *et al.* [20] tackled the problem of maximizing the total normalized spatiotemporal coverage (NSTC) under a limited budget using a scenario with three types of RSUs: 1) static, 2) public transportation, and 3) fully controllable vehicles. Their focus was to find the optimal route of the controlled vehicles in order to maximize total coverage. However, their results are vague in the perspective of the network. This is because a route is considered 'covered' if a mobile RSU passes through that route at a certain time without consideration of network performance.

Finally, although we focus on the IEEE 802.11p-based dedicated short range communication (DSRC) technology, there is another recent proposal to use long term evolution (LTE) based LTE-V2X (a.k.a C-V2X) for V2X communication [21]–[24]. In general, LTE-V2X aims for supporting a wider communication range and higher data rates [21], [22] while DSRC, as its name implies, is dedicated for robust communication over a shorter range with different use cases [23], [25]–[28]. Furthermore, despite the proposal being standardized by 3GPP in Release-14 recently, there is no prototype platform nor implementation for LTE-V2X available yet where as DSRC is under an active pilot program at the US Department of Transportation [29].

To the best of our knowledge, there is no in-depth study of how mobile RSUs should be deployed and used according to various performance and cost requirements, and none of the aforementioned papers show results from real experiments. Thus, this paper aims to provide an insight into how buses can be used as mobile RSUs in various scenarios, requirements, and costs, through mathematical analysis, simulation, and real-world experiments.

III. Scenarios and Problem Statement

Mobile RSUs have several advantages that compensate for the limitations of static RSUs. By adjusting the number of mRSUs, one can easily adjust the total number of RSUs in the system as needed, such as traffic volume by time of day. If an mRSU fails, it can be replaced promptly and repaired at the same place (e.g. bus parking lot) without having to go directly to each location, reducing maintenance costs. Moreover, it has been shown that the maximum transmission range and frame loss ratio of IEEE 802.11p [30] is affected more by the relative velocity than absolute velocity of the vehicles [31], [32]. Thus, when an mRSU and a car travel in the same direction, there is a better chance of mRSU having longer contact time with the car than the sRSU, leading to more stable service. The car can select an RSU that is expected to have the longest contact time among neighboring RSUs by using navigation and direction information.

In addition, utilizing buses as mRSUs has several additional advantages compared to using other vehicles.

- Buses have fixed routes and schedules. Thus, the expected spatio-temporal coverage and service quality can be predicted to provide a more stable service.
- Using public (authorized) buses can be made more secure than using anonymous vehicles. They can be pre-authenticated using secure techniques such as public key cryptography.
- Line-of-sight (LoS) condition is strongly desirable for better packet delivery ratio (PDR) [33], especially for IEEE 802.11p. Since buses are taller than other cars, it is easier to provide LoS in all directions.
- Buses can carry larger communication equipment with greater capacity and memory than conventional vehicles, providing more reliable service.

Despite these potential advantages, we ask the following questions: (1) can bus-based mRSUs replace sRSUs? (2) how many mRSUs would be needed to replace one sRSU? (3) what would be the overall performance after replacement? Buses move according to traffic volume, speed, traffic signals, bus stops, and road conditions. They can potentially provide more stable service due to the long contact time with nearby cars when moving together in the same direction, but they may not able to serve the cars which are moving in the same direction and outside the range for a long time.

To this end, we believe that a practical system would comprise a mix of mRSUs and sRSUs to take advantage of both sides. We use sRSUs as a backbone for reliable and stable roadside service, even during the night times, and add mRSUs to increase coverage, alleviate service bottleneck, and reduce the total number of sRSUs required to support the same level of performance even during the rush hours. mRSUs will provide a better connectivity to vehicles traveling along in the same direction (or stuck together in traffic jam), and sRSUs will guarantee minimum level of connectivity at regular intervals.

Based on the above intuition, we consider and compare two schemes, *'sRSU only'* and *'mRSU+sRSU'* schemes in this work. Given an area of interest and its road span distance L, suppose there are N_s sRSUs statically deployed along the roads at regular intervals in the 'sRSU only' scheme. For the 'mRSU+sRSU' scheme, we reduce the number of sRSUs to N_s/n, and add mRSUs at a *replacement ratio* of r relative to the number of replaced sRSUs, N_s/n. Thus, the total number of RSUs in the 'sRSU only' scheme is N_s, and it is $\frac{1+(n-1)r}{n}N_s$ for the 'mRSU+sRSU' scheme. They are equal when r is 1.

Note that r represents the ratio of the average number of mRSUs (relative to the number of replaced sRSUs, N_s/n) in the area of interest during the observation time, and thus may not be an integer considering the temporal interval between mRSUs (i.e. buses moving in and out of the area of interest). If r equals 1, we are replacing a sRSU with one mRSU 1-to-1, and if $r = 2$, we need twice as many mRSUs than the number of sRSUs we replaced. For example, if $N_s = 100$ and $n = 2$, then our problem statement simplifies to, *"compared to a system with 100 sRSUs, if we were to reduce the number of sRSUs to 50, then how many mRSUs would we need to equal the average network performance?"*. This is what we investigate and answer in the remainder of this manuscript.

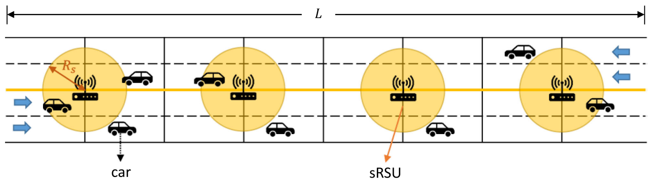
Finally, we note that in our system and usage scenario, an mRSU accesses the core network using a cellular network (e.g. LTE, 5G). For delay tolerant information, the mRSU updates information using DSRC when it contacts a sRSU. If we use a subset of bus stations as sRSUs, we have enough time to update the information for the mRSU while the mRSU (i.e. bus) stops at stations. We believe that this approach is less expensive than wired sRSU, including installation, management and usage costs. Furthermore, using a cellular network for mRSUs is not an unrealistic vision. There are already pilot/prototype services which equip buses with high bandwidth cellular communication for future autonomous driving and smart vehicular networks.[1]

IV. Analysis

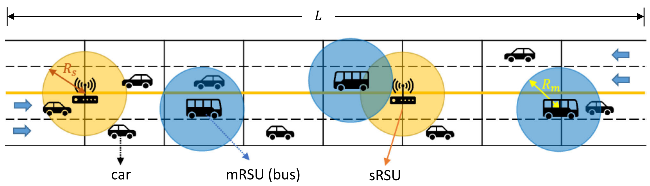
We mathematically analyze the average contact time of cars to RSUs for the two schemes described in Section III. Contact time refers to the amount of time the car has been in contact with an RSU while passing through the area of interest. Using the contact time for both schemes, we find the number of mRSUs required to equivalently replace one sRSU.

To keep our mathematical analysis tractable, we consider a straight two-way road scenario where cars start in both directions and go straight, travel for a distance L, and go out at the opposite side. If there are no opposite direction cars and mobile RSUs, it can be regarded as a one-way road scenario. Since more complicated scenarios including intersection scenario or circular road scenario are not tractable for mathematical analysis, we show simulation results for Manhattan scenario alternatively. Fig. 1 illustrates the two-way road scenario used in this section, and Table I lists the key system parameters that are used in this paper.

[1] https://www.kt5gbus.com:8080/



(a) 'sRSU only' scheme



(b) 'mRSU+sRSU' scheme

Fig. 1. Examples of two-way straight road scenario where cars communicate with an RSU within the range while driving.

TABLE I
SYSTEM PARAMETERS

Parameter	Description
N_s	Number of static RSU in 'sRSU only' scheme
N_m	Number of mobile RSU in 'mRSU+sRSU' scheme
R_s	Transmission radius of static RSU
R_m	Transmission radius of mobile RSU
v_c	Velocity of car
v_m	Velocity of mobile RSU
L	Total road span length in area of interest

A. 'sRSU only' Scheme

In the 'sRSU only' scheme, there are N_s sRSUs deployed on the road of length L, and no mRSU. The distance between sRSUs need not necessarily be regular, but should be at least $2R_s$. Since the sRSUs are stationary, the average contact time of the cars, T_s, can be obtained as the time it takes for a car to pass through the transmission area of N_s sRSUs. Then, T_s can be expressed as,

$$T_s \approx \mathbb{E}\left[N_s\frac{2R_s}{v_c}\right] = 2R_sN_s\mathbb{E}\left[\frac{1}{v_c}\right]. \tag{1}$$

Note that, since we are considering a linear topology scenario where the transmission range R_s (usually larger than 100 m) is sufficiently longer than the width of a road (approximately 3.5 m), we can simplify the circular transmission range into a 1-dimensional problem.

B. 'mRSU+sRSU' Scheme

In the 'mRSU+sRSU' scheme, we reduce the number of sRSUs to N_s/n and add $N_m = r \cdot N_s(n-1)/n$ mRSUs for $n > 1$. Then the average inter-sRSU distance is $n{\cdot}L/N_s$. For the mRSUs, since N_m buses move in both directions, there are $N_m/2$ buses on each direction.

Under this setup, cars can be in contact with either sRSUs or mRSUs. The average contact time of the cars, T_m, can then be obtained as the time it takes for a car to pass through the transmission area of either N_s/n sRSUs or N_m mRSUs. In other words, T_m is the total traveling time for a distance L, excluding the time for the car to be outside the transmission range of sRSUs, mRSUs in the same direction, and mRSUs in the opposite direction. Then, we obtain T_m as,

$$\begin{aligned}
T_m &\overset{(a)}{=} T_L(1 - P^s_{nct}P^f_{nct}P^r_{nct}) \\
&\overset{(b)}{\approx} \mathbb{E}\left[\frac{L}{v_c}\right] \\
&\quad \times \left(1 - \left(1 - \frac{2R_sN_s}{nL}\right)\left(1 - \frac{R_mN_m}{L}\right)\left(1 - \frac{R_mN_m}{L}\right)\right) \\
&= \mathbb{E}\left[\frac{1}{v_c}\right]\left(L - \left(L - \frac{2R_sN_s}{n}\right)\left(1 - \frac{R_m}{L}N_m\right)^2\right),
\end{aligned} \tag{2}$$

where T_L is the time for passing L, and P^s_{nct}, P^f_{nct}, and P^r_{nct} are the probabilities that a car is outside the range of sRSUs, of mRSUs in the same direction, and of mRSUs in the opposite direction, respectively. (a) follows since the average contact time, which is the time a car spends in the range of either sRSUs or mRSUs, can be calculated using the probability that the car is outside the range of neither sRSUs and mRSUs. (b) comes from,

$$P^s_{nct} = \frac{L - 2R_s \cdot \frac{N_s}{n}}{L} \tag{3}$$

$$P^f_{nct} = \frac{(L - 2R_m \cdot \frac{N_m}{2})/(v_c - v_m)}{L/(v_c - v_m)} = \frac{L - R_mN_m}{L} \tag{4}$$

$$P^r_{nct} = \frac{(L - 2R_m \cdot \frac{N_m}{2})/(v_c + v_m)}{L/(v_c + v_m)} = \frac{L - R_mN_m}{L}. \tag{5}$$

As P^s_{nct}, P^f_{nct}, and P^r_{nct} are probabilities, they are greater than or equal to 0, which means $L \geq 2R_sN_s/n$, and $L \geq R_mN_m$. When $L \leq 2R_sN_s/n$, P^s_{nct} becomes 0. Whereas, if $L \leq R_mN_m$, P^f_{nct} and P^r_{nct} become 0. If one or all of the conditions are met, $T_m = T_L$ in Eq.(2), which means the RSUs fully cover the area of interest.

C. Normalized Contact Time

To show the performance with added mRSUs compared to that with sRSUs only, we calculate normalized contact time, T_n. It is the contact time of 'mRSU+sRSU' scheme divided by that of 'sRSU only' scheme. We have T_n as,

$$T_n = \left(L - \left(L - \frac{2R_sN_s}{n}\right)\left(1 - \frac{R_m}{L}N_m\right)^2\right)/2R_sN_s. \tag{6}$$

The normalized contact time of 1 means that the performance of 'sRSU only' and 'mRSU+sRSU' schemes are identical.

The relationship between the replacement ratio r and T_n can be found by differentiating the equation. As the replacement ratio can be denoted as $r = \frac{nN_m}{(n-1)N_s}$, we rewrite Eq.(6) as,

$$T_n = \left(L - \left(L - \frac{2R_sN_s}{n}\right)\left(1 - \frac{(n-1)R_m}{nL}N_sr\right)^2\right) \Big/ 2R_sN_s. \tag{7}$$

Assuming that L, R_s, R_m, N_s are constants, and differentiating T_n with r, we obtain T_n' as,

$$T_n' = \frac{(n-1)(L-2R_sN_s/n)R_m}{nR_sL}\left(1 - \frac{(n-1)R_mN_sr}{nL}\right). \tag{8}$$

Since, $n-1$, L, R_s, R_m, and N_s are all positives, and $L \geq 2R_sNs/n$, $L \geq R_mN_m$, T_n' is non-negative. We can see that T_n increases with r.

T_n'', which is obtained by differentiating T_n twice, can be expressed as,

$$T_n'' = -\frac{(n-1)(L-2R_sN_s/n)R_m}{nR_sL}\left(\frac{(n-1)R_mN_s}{nL}\right). \tag{9}$$

Since T_n'' is non-positive, as r increases, T_n's rate of increase becomes smaller. This is due to the increase of mRSUs in the area of interest which causes the mRSUs to overlap more frequently.

D. Equalizing Replacement Ratio

Now, when we replace $(n-1)N_s/n$ sRSUs with mRSUs, we calculate the replacement ratio of mRSUs per sRSU that would provide the contact time equivalent to that of the 'sRSU only' scheme (i.e. when $T_n = 1$). We name this ratio as the *equalizing replacement ratio*, r_e. Then, we derive r_e by letting $T_n = 1$;

$$\left(L - \left(L - \frac{2R_sN_s}{n}\right)\left(1 - \frac{R_m}{L}N_m\right)^2\right) = 2R_sN_s. \tag{10}$$

Substituting N_m for $(n-1)N_sr_e/n$, we obtain r_e as,

$$\left(1 - \frac{(n-1)R_mN_s}{nL}\cdot r_e\right)^2 = \frac{L-2R_sN_s}{L-2R_sN_s/n} \tag{11}$$

$$r_e = \frac{nL}{(n-1)R_mN_s}\left(1 - \sqrt{\frac{L-2R_sN_s}{L-2R_sN_s/n}}\right) \tag{12}$$

This draws an important point: If the cost of an mRSU is less than $1/r_e$ times that of a sRSU, equivalent contact time performance can be achieved while using the mRSU at a lower cost. Our results show that the normalized contact time and the equalizing replacement ratio are not affected by the speed of vehicles nor traffic volume but by the average sRSU interval, L/N_s, n, and the transmission ranges R_s and R_m. That is, if the area covered by sRSUs becomes larger, more mRSUs are needed to achieve equivalent performance compared to the scheme of using sRSUs only. Also, more mRSUs are needed when the transmission range of each mRSU is smaller.

Fig. 2 shows r_e according to N_s and n when L is 6 km, and both R_m and R_s are 0.25 km. When the area covered by sRSU is small (i.e. small N_s or large n), there is no significant difference in r_e according to n.

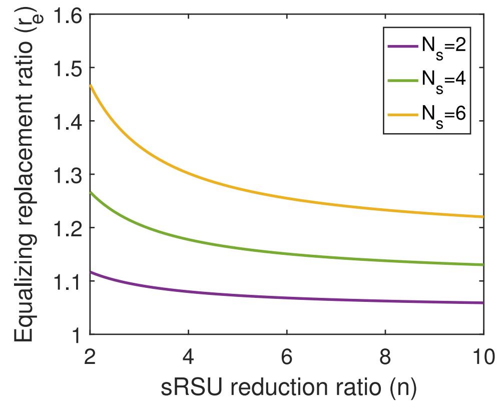


Fig. 2. Equalizing replacement ratio, r_e according to N_s and n.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Packet size	613 bytes
Transmission power	20 dBm
Maximum transmission range R_s, R_m	250 m
Frequency	5.9 GHz
Channel bandwidth	10 MHz
Data rate	6 Mbps
Average speed of cars v_c	50 km/h
Speed of a bus v_b	30 km/h
Simulation time	3600 s
sRSU reduction ratio n	2

V. PERFORMANCE EVALUATION

We evaluate and compare the network performance of the system with and without mRSUs ('mRSU+sRSU' and 'sRSU only' schemes), with varying degree of replacement ratios, by carrying out trace-driven network simulations in various environments. We first cover the identical two-way straight road scenario as our analysis in Section IV to validate the results. Secondly, considering that the mathematical analysis is done under a simplified setting, we extend the scenario to include traffic lights and bus stops in order to replicate a more realistic two-way straight road. Finally, we implement a large scale, urban grid road environment simulation on the city of Manhattan to evaluate performance under a realistic and mathematically intractable scenario.

A. Simulation Setup

Road topology and vehicle mobility for simulations are created using the SUMO simulator [34], which generates traces that can be fed as input to the NS3 network simulator [35]. Then, NS3 simulation was conducted to obtain the network performance results. IEEE 802.11p based DSRC was used for V2X communication.

Table II summarizes the simulation parameters. In simulation, we assume that performance specifications of mRSU and sRSU are the same, and thus their transmission power and maximum transmission range are equal to 20 dBm and 250 m, respectively. Average speed of the cars and the buses are determined by their running speed in normal operation without congestion or stops. The speed of cars follows a truncated normal distribution where the maximum and minimum speeds are 120% and 80% of the average speed, respectively. A bus moves at a constant speed except when it stops at bus stations, traffic lights, or when the roads are congested since we believe that a bus would travel at a relatively constant speed than a car. The sRSU reduction ratio n is set to 2 which indicates that the number of sRSUs is halved in the 'mRSU+sRSU' case compared to 'sRSU only' case.

B. Performance Metrics

We use three performance metrics for evaluation.

Normalized contact time: To measure contact time in our simulation, RSUs are configured to broadcast a beacon packet every second. Then, the reception of these packets at the cars are the indirect measure of *contact time*. To simulate packet reception, we used the range propagation loss model with default reception range of 250 m. Then, *average contact time* is the total number of packets that cars receive divided by the number of cars that pass through the area of interest during the simulation time. When the transmission ranges of multiple RSUs overlap, packets from only one RSU are counted towards the contact time. In our simulations, a vehicle receives information from a RSU that it contacts first, but other policies can be adopted to filter out duplicate messages (e.g., signal strength and minimum distance). Finally, *normalized contact time* is the contact time of 'mRSU+sRSU' scheme normalized (divided) by that of 'sRSU only' scheme.

Inter-contact time: Inter-contact time refers to the time interval between contacts, equivalent to the disconnection time between two RSU encounters. Since an RSU sends one packet per second and a car that receives the packets moves contiguously towards or away from the RSU, the interval between two adjacent packets is approximately one second when the packets are continuously received. Thus, if the inter-packet interval is 2 seconds or greater, it is assumed that the contact between the car and an RSU is disconnected, and the inter-packet interval becomes the inter-contact time. When a car is disconnected from the RSU and takes a long time to re-connect, the inter-contact time becomes longer which indicates that there is a large delay in receiving the desired data.

Normalized throughput: For the measurement of *throughput*, RSUs are configured to broadcast a data packet every 100 ms, and the total number of successfully received packets at the cars during the simulation time is used. Similar to the normalized contact time, we calculated the *normalized throughput* by dividing the number of packets in the 'mRSU+sRSU' scheme by that of the 'sRSU only' scheme.

To take packet loss into consideration, we applied the *log-distance propagation loss model* suitable for urban environments [36], and the *nakagami-m fading model* which considers multipath fading. Using the log-distance propagation loss model, path loss PL can be represented as

$$PL = PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right), \tag{13}$$

where the path loss distance exponent n is 2.7 which is suitable for urban environments [37], reference distance d_0 is 1 m, and the path loss at reference distance (1 m) PL_0 is 46.67 dB in the simulation [35].

The probability density function of nakagami-m fading model is expressed as

$$P(x; m, w) = \frac{2m^m}{\Gamma(m)w^m} x^{2m-1} e^{\frac{-m}{w}x^2}, \tag{14}$$

where m is the fading depth parameter, w is the average received power, and Γ denotes the gamma function. We specify different values of the m parameter for different distance ranges. In simulation, m is 1.5 at 80 m or less, and 0.75 beyond 80 m [36].

C. Two-Way Road Scenario

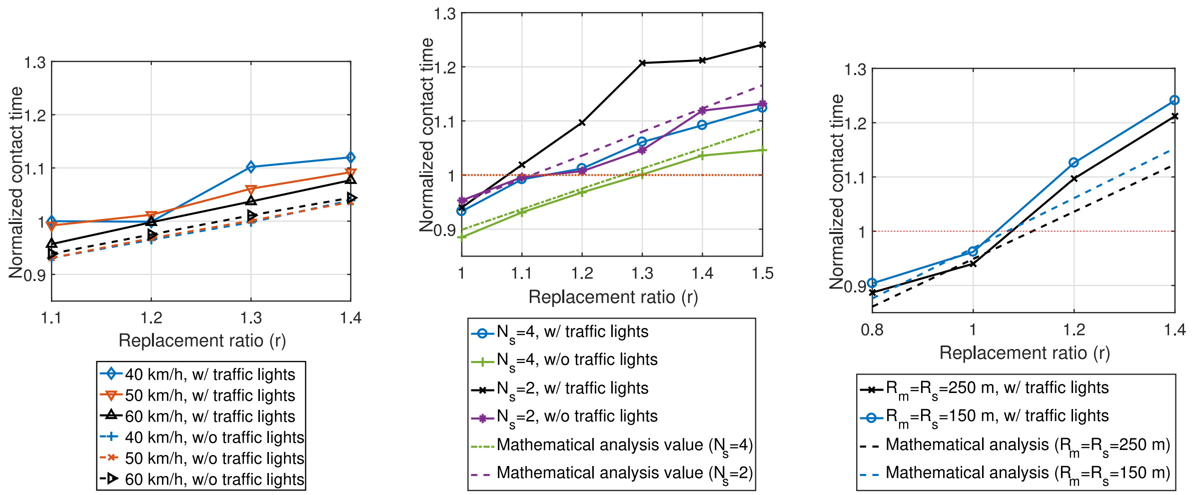
We first perform simulation on the two-way straight road scenario as shown in Fig. 1. This is identical to the setup of our analysis in Section IV, and most of the parameters are selected to mimic those of the analysis. Distance between neighboring traffic lights is 300 m, and red and green lights alternate every 30 seconds. The total length of the area of interest (L) is 6 km and bus stations are installed every 500 m at which a bus stops for 10 seconds. Stop time of the bus is chosen based on our measurements on two real bus lines for 10 days, where the average was 10.99 seconds. Under this setup, we first perform simulation without traffic lights as it is done in Section IV, and also with traffic lights to produce a more practical condition.

The sRSUs are installed every L/N_s km in 'sRSU only' scheme. When using mRSUs, sRSU interval is $2L/N_s$, since the number of sRSUs is halved. By changing the sRSU interval, we can adjust the sRSU density (i.e. space coverage ratio of sRSU). Cars come out from one side and move to the other. The buses alternate on both sides with the same dispatch interval. Cars are generated alternately in both directions, one every 5 seconds on average.

The difference in departure time between buses in both directions is crucial because it affects their relationship and thus bring about different results in the contact time. Taking this into account, we let bus start time be uniform randomly distributed within the bus interval, and run the simulation five times. The simulation time is 3600 seconds for each starting point and 18000 seconds in total. Since there is no bus on the road at first, we begin measuring performance after a certain period of time to allow some time for the road to have a traffic condition that is more similar with that of a real-life situation.

In Section IV, we derived that the speed of cars does not affect the normalized contact time and equalizing replacement ratio. To prove this, we look at the normalized contact time with various average car speeds, 40 km/h, 50 km/h and 60 km/h when N_s is 4. Fig. 3(a) indeed shows that without traffic lights, the normalized contact time and equalizing replacement ratio are not affected by the speed of cars. When with traffic lights, lower speed of cars tends to show longer contact time because cars are more likely to stop at the traffic lights with the RSUs.

We also found in Section IV that the number of sRSUs affects equalizing replacement ratio. Less number of sRSUs per unit distance (lower density) makes the equalizing replacement ratio smaller. Fig. 3(b) plots the normalized contact time in two



(a) With varying car speeds (40 km/h, 50 km/h, and 60 km/h) when $N_s = 4$, with or without traffic lights

(b) With two RSU densities ($N_s = 4$ and $N_s = 2$), with or without traffic lights

(c) With two transmission ranges ($R_s = R_m = 250$ m and $R_s = R_m = 150$ m), with traffic lights when $N_s = 2$

Fig. 3. Normalized contact time under various environments and configurations.

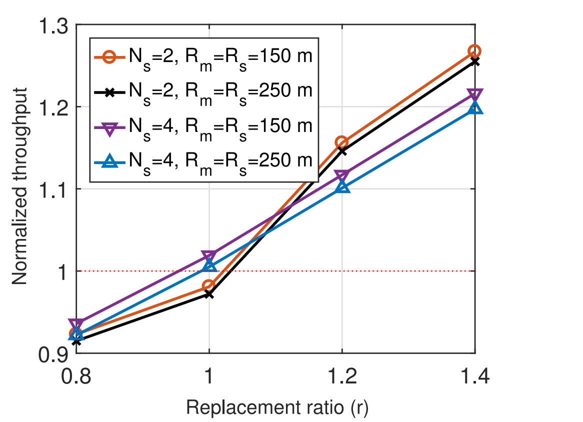


Fig. 4. Normalized throughput with various RSU densities ($N_s = 4$ and $N_s = 2$) and various transmission ranges ($R_s = R_m = 250$ m and $R_s = R_m = 150$ m).

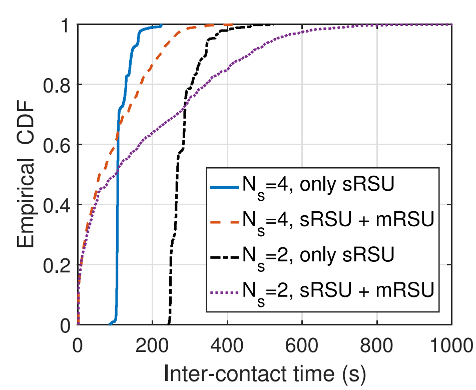


Fig. 5. Empirical CDF of inter-contact time with traffic lights in various sRSU densities ($N_s = 4$ and $N_s = 2$).

different sRSU densities with four sRSUs and two sRSUs in the area of interest respectively. Both sRSU densities show similar results with mathematical analysis when there are no traffic lights, but show larger normalized contact time when there are traffic lights. The reason of this is that in the case of sRSUs, the contact time with the cars is increased only when the cars stop at the traffic lights near the sRSUs, but mRSUs are more likely to stop at the traffic lights *together* with the cars while traveling which notably increases the contact time.

We also examine the contact time according to the transmission range of the RSUs. Fig. 3(c) depicts the normalized contact time in two different transmission ranges of the RSUs; 150 m and 250 m. As the range of RSUs becomes smaller, the probability of coverage overlap goes down, which improves the normalized contact time performance and lower the equalizing replacement ratio when using mRSUs.

Fig. 4 shows the normalized throughput for two different RSU densities ($N_s = 2$ and $N_s = 4$) and two different transmission ranges (150 m and 250 m) of RSUs, with traffic lights. In the case of throughput, the equalizing replacement ratio r_e is smaller than that of the contact time under the same conditions. This indicates that a smaller number of mRSUs is needed to match the throughput performance than what needed to match the contact time. In layman's terms, you can easily achieve the same throughput performance with less number of mRSUs while you need more to achieve the same contact time performance.

Packet loss increases as the distance between the RSU and the car increases. In the case of mRSU moving in the same direction as a car, the car takes a long time to contact the mRSU on average, but once in contact, it can be connected for a long time since they are likely to travel in proximity. On the other hand, when the mRSU is moving in the opposite direction to the car, the contact time between the car and the mRSU is very short and its contribution on the throughput is small. For these reasons, although normalized throughput shows similar tendency as normalized contact time, the number of mRSUs required to achieve the same throughput as 'sRSU only' is less than contact time.

We also analyze the changes in inter-contact time. Fig. 5 plots the empirical cumulative distribution function (CDF) of the inter-contact time at various replacement ratios. We set the replacement ratios to 1.2 and 1.1 when N_s is 4 and 2 respectively. As N_s increases, the interval between sRSUs decreases and N_m increases at the equalizing replacement ratio which makes the degradation of the inter-contact time. The inter-contact time is almost constant in the ‘sRSU only’ scheme and greatly varies in the ‘mRSU+sRSU’ scheme. We can see that the use of mRSU significantly changes the inter-contact time even though it shows the same contact time with that of ‘sRSU only’ scheme on average. However, since ‘mRSU+sRSU’ scheme uses $N_s/2$ sRSUs, the maximum inter-contact time does not exceed twice of that in the ‘sRSU only’ scheme. That is, sRSUs complement the disadvantages of using mRSUs by bounding the inter-contact time variation of the mRSUs. This result shows that our decision to use both mRSU and sRSU is appropriate.

In summary, the equalizing replacement ratio is about 6% lower than that of the mathematical analysis in the realistic environment with traffic lights and bus stops. For throughput, the equalizing replacement ratio is about 6% lower than that of the contact time. From these results, we find that the mathematical analysis provides the upper bound of the equalizing replacement ratio. It is a good option to use the upper bound as a reference because the inter-contact time fluctuate more when using mRSU than when using sRSU alone. Therefore, we can conclude that, if the cost of the mRSU is less than $1/r_e$ times the cost of the sRSU, then using the mRSUs will yield better performance than using only the sRSUs at a lower cost.

D. Manhattan Scenario

In cities, straight roads and intersections are combined to form a grid pattern. To see more comprehensive results in such a realistic urban area, map and bus routes of Manhattan, New York City is used as our second simulation scenario. Since it has grid pattern roads and several bus lines, it is well-suited for our purposes.

First, we export a map of Manhattan from OpenStreetMap.[2] Fig. 6 shows the area used in simulation.[3] Eight bus lines, M1, M12, M15, M20, M21, M23, M31 and M42, in Fig. 6 are used for simulation where their detailed route information is summarized in Table III. The length of the bus line and the number of bus stations in the table are only for the parts within the simulation area of interest. We use the maximum value of bus dispatch interval during weekdays as the bus dispatch interval, and set the traffic lights and speed limits of each street as their actual values obtained from the map.

In the ‘sRSU only’ scheme, sixteen sRSUs are in the positions shown in Fig. 6, and in the ‘mRSU+sRSU’ scheme, eight sRSUs are removed alternately from the top right of the figure and eight bus lines are added. The removed sRSUs are indicated by dotted lines in Fig. 6. Due to the bus dispatch intervals, average number of buses in the area of interest at a time is 13.6, which means that the replacement ratio is 1.7. RSUs broadcast packets every 1 second and the transmission range is 250 m. We measure the average number of received packets per car during 3600 seconds.

[2]OpenStreetMap, https://www.openstreetmap.org/

[3]Manhattan bus lines: http://web.mta.info/nyct/maps/manbus.pdf

Fig. 6. Map of the Manhattan scenario for ‘sRSU only’ scheme. For ‘mRSU+sRSU’ scheme, eight sRSUs are removed alternately and buses from eight bus lines are added as mRSUs.

TABLE III
BUS ROUTE INFORMATION

Bus line	length (km)	Number of bus stations	Dispatch interval (minute)
M1	8.9	42	25
M12	11.3	42	30
M15	10.9	44	15
M20	11.4	50	30
M21	8.2	42	30
M23	7.8	30	20
M31	6.9	28	20
M42	6.5	31	20

TABLE IV
AVERAGE NUMBER OF RECEIVED PACKETS PER CAR

	sRSU	mRSU	total
sRSU only	180.80	-	180.80
mRSU+sRSU	104.89	174.97	279.86

Average distance between two adjacent sRSUs is about 1.5 km and the total length of the bus routes is 71.9 km. Since all bus routes are roundtrip, we can say that the total length of the area of interest is 35.95 km. If we apply these numbers into Eq.(6), normalized contact time is 1.22.

Total of 5025 randomly moving cars are simulated in the Manhattan scenario. Table IV shows the average number of received packets per car. On average, vehicles in the ‘mRSU+sRSU’ scheme receive 1.55 times more packets than the ‘sRSU only’ scheme. This result represents the improvement in normalized throughput since we measure throughput by counting the number of received packets per unit time.

Similar to the two-way road scenario, the normalized throughput is larger than the normalized contact time obtained through mathematical analysis. This indicates that our mathematical

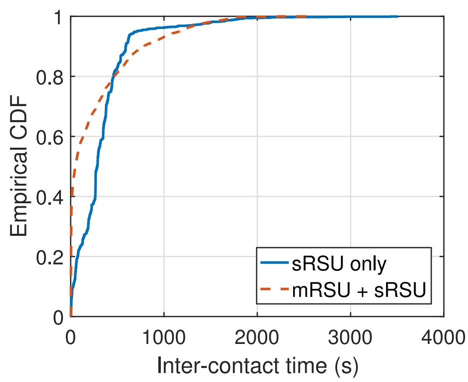


Fig. 7. Empirical CDF of inter-contact time in Manhattan scenario.

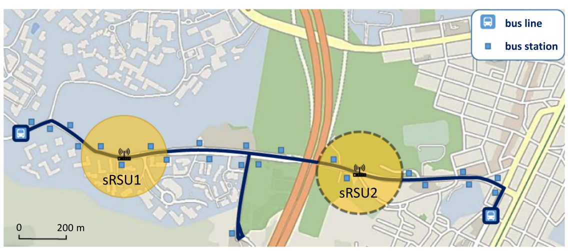


Fig. 8. Map of the real-world experiment setup: two-way road of length 5.8 km with 23 bus stations and 16 traffic lights.

Fig. 9. DSRC module and antenna setting for the real-world experiment.

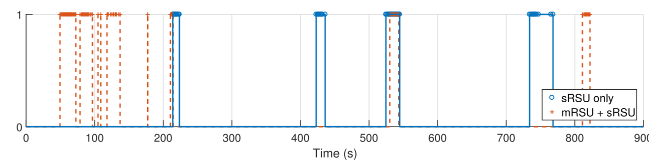


Fig. 10. Packet reception example of Car1 during 900 s experiment.

TABLE V
NUMBER OF RECEIVED PACKETS

	sRSU1	sRSU2	mRSU	total
sRSU only	268	107	-	375
mRSU+sRSU	274	-	203	477

analysis without traffic lights provide an upper bound of equalizing replacement ratio also in the large-scale grid Manhattan scenario in line with the two-way road scenario.

Fig. 7 shows the empirical CDF of inter-contact time. In most cases, similar to the two-way road scenario, inter-contact time of the 'sRSU only' scheme is relatively constant while that of the 'mRSU+sRSU' scheme varies significantly. However, around 5% of the inter-contact times in the 'sRSU only' scheme show noticeably large value. This is because, unlike the two-way road scenario, Manhattan scenario has several roads and intersections in a grid pattern. If a car travels for a long time on roads that sRSUs do not cover, it will not be able to receive packets for a long time. From this result, we can see that the use of mRSU in the urban grid environment does not significantly reduce the performance in terms of inter-contact time fluctuation.

VI. REAL-WORLD EXPERIMENT

In the earlier sections, we covered the mathematical analysis and NS3+SUMO based simulations. In this section, we aim to corroborate the results from those two with a real-world experiment. Although the scale of our experiment cannot match that of the simulation study due to practical constraints, our goal is to provide performance results using real devices on real vehicles in less-controlled environments. We hope to provide a realistic view of the problem, as well as lessons learned from our experiences.

Fig. 8 shows the map of our experiment area including the bus line, bus stations, and the location of sRSUs used in the experiment. The length of the bus route is 5.8 km, and there are 23 bus stations and 16 traffic lights in the area of interest. The distance between the traffic lights are around 300 meters, and the red light and green light alternate every 30 seconds. For the 'sRSU only' scheme, two sRSUs (sRSU1 and sRSU2) are installed as shown in Fig. 8, while the sRSU2 is replaced by a bus for the 'mRSU+sRSU' scheme. As one bus-mRSU is used instead of one sRSU, and because of the time delay it takes for a human to transfer to another bus at the ends of the route, the replacement ratio is 0.8125 on average in the 'mRSU+sRSU' scheme. Finally, two cars are used to receive packets from the RSUs and measure network performance while moving back and forth along the route for an hour.

For the communication hardware, we use IT-telecom vad-sh2 DSRC devices. Among the four devices we use, two are installed in the cars as OBUs to receives packets from the RSUs. The antenna is mounted on the car and the DSRC module is placed inside the car as shown in Fig. 9. The other two devices work as RSUs, either installed on the road as sRSU(s), or placed on the bus as an mRSU. When configured as a RSU, it transmits 613-byte data packets every second. We use channel 172 with 10 MHz bandwidth at frequency range 5.855 GHz $\sim$ 5.865 GHz with 6 Mbps datarate. Transmission power is set to 20 dBm, which provides a transmission range of approximately 150 meters in line-of-sight condition.

Fig. 10 plots the packet reception pattern of Car1 for 900 seconds to provide a brief example. The y-axis values of 1 and 0 indicate whether a packet has been received or not, respectively, and the lines indicate whether the car was in contact with an RSU. If the interval between two packet receptions is within 5 seconds, it is assumed that the car is in contact with an RSU. Note that the contact time of 'sRSU only' scheme is significantly shorter with more frequent and periodical intervals than that of the 'mRSU+sRSU' scheme.

Table V shows the total number of packets received by the cars for the two schemes during the experiment. More packets

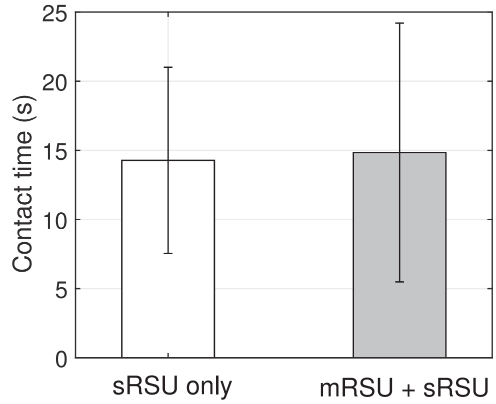


Fig. 11. Contact time from the experiment when inter-packet time is within 5 seconds.

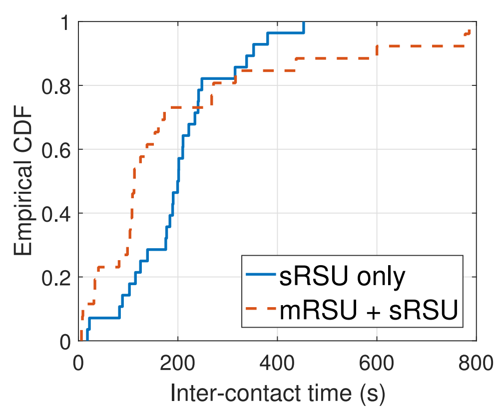


Fig. 12. Empirical CDF of inter-contact time. We assume that a contact is disconnected when inter-packet time is over 5 seconds.

are received when there is an mRSU (bus) with an sRSU than when there are two sRSUs only despite the fact that there were only 1.8125 RSUs on average for the 'mRSU+sRSU' scheme considering the temporal absence. In the 'sRSU only' scheme, the cars receive more packets from sRSU1 than sRSU2. This is due to the surrounding environment and road condition at which the sRSUs are installed. sRSU1 is located in a relatively LoS environment while sRSU2 is not due to the surrounding terrain. Furthermore, road condition near sRSU1 is worse, forcing the cars to slow down and allowing them to pick up more packets while road condition near sRSU2 fares better, letting cars increase their speed and losing time to receive packets. However, the road condition does not affect the mRSU as much because the mRSU moves at a similar pace with nearby cars.

As shown in Fig. 11, the mean and variance of the contact time of the 'mRSU+sRSU' scheme is larger than that of 'sRSU only'. This shows that although the 'mRSU+sRSU' scheme has longer contact time than the 'sRSU only' on average, the cars have a varying contact time while they have more regular intervals in the 'sRSU only' scheme. This is because the cars contact the bus in the same direction for a longer time than with the bus in the opposite direction.

In Section V, simulation results have shown that the inter-contact time varies more with the 'mRSU+sRSU' scheme than the 'sRSU only' scheme. Similar to the simulation results, Fig. 12 shows the empirical CDF of the inter-contact time from our experiments where the 'mRSU+sRSU' scheme exhibits more variance between its values while the 'sRSU only' scheme is more uniform. This is because the sRSUs are fixed in the 'sRSU only' scheme whereas the contact time varies significantly due to bus mobility, bus and car direction, traffic lights, and bus stations in the 'mRSU+sRSU' scheme.

VII. Conclusion

Roadside units are one of the key components for future safe and autonomous vehicular networks. In this work, we explored the utility and trade-off of using buses as mobile RSUs through mathematical analysis, simulation, and real-world experiments. We reduced the number of sRSUs by replacing them with buses, and compared the performance in terms of contact time, inter-contact time and throughput as a function of replacement ratio. We analyzed the equalizing replacement ratio that yields the same performance as when using only sRSUs, and found conditions that do or do not affect the ratio. Our results provide an upper bound on the equalizing replacement ratio which can be used as a guideline to determine the use of mRSUs in terms of cost and performance trade-offs.

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Jeongyoon Heo received the B.S. degree in electrical engineering from Korea University, Seoul, South Korea, in 2013. She is currently working toward the Ph.D. degree at the School of Computer Science and Electrical Engineering, Seoul National University, Seoul, South Korea. Her research interests include the area of security and energy efficiency in wireless networks, Internet of Things, and also in the area of vehicle-to-everything (V2X) including localization and security.

Byungjun Kang received the B.S. and the M.S. degrees both in electrical engineering from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, in 2013. He is currently working toward the Ph.D. degree at the School of Computer Science and Electrical Engineering, Seoul National University, Seoul, South Korea. His research interests include the area of information theory and resource management in wireless networks including device-to-device (D2D) and vehicle-to-everything (V2X) communications.

Jin Mo Yang received the B.S. degree in electronic engineering from Hanyang University, Seoul, South Korea, in 2018. He is currently working toward the master's degree in electrical and computer engineering at Seoul National University. His research interests include vehicle-to-everything (V2X) communication.

Jeongyeup Paek received the B.S. degree from Seoul National University, Seoul, South Korea, in 2003 and the M.S. degree from the University of Southern California, Los Angeles, CA, USA, in 2005, both in electrical engineering. He received the Ph.D. degree in computer science from the University of Southern California in 2010. He is currently an Associate Professor at Chung-Ang University, School of Computer Science and Engineering, Seoul, South Korea. He worked at Deutsche Telekom, Inc., R&D Labs USA as a Research Intern in 2010, and then joined Cisco Systems, Inc. in 2011, where he was a Technical Leader in the Internet of Things Group, Connected Energy Networks Business Unit (formerly the Smart Grid Business Unit). In 2014, he was with the Hongik University, Department of Computer Information Communication as an Assistant Professor.

Saewoong Bahk received the B.S. and M.S. degrees in electrical engineering from Seoul National University, Seoul, South Korea, in 1984 and 1986, respectively, and the Ph.D. degree from the University of Pennsylvania, Philadelphia, PA, USA, in 1991. He is currently a Professor at Seoul National University. He was the Director of the Institute of New Media and Communications during 2009–2011. Prior to joining SNU, he was with AT&T Bell Laboratories as a member of technical staff from 1991 to 1994 where he had worked on network management.He has been leading many industrial projects on 3G/4G/5G and IoT connectivity supported by Korean industry, and published more than 200 technical papers and holds more than 100 patents. He has been serving as the Chief Information Officer of SNU, the General Chair of IEEE DySPAN 2018 (Dynamic Spectrum Access and Networks), the General Chair of IEEE WCNC 2020 (Wireless Communication and Networking Conference), and the Director of Asia-Pacific region of IEEE ComSoc. He is President-Elect of the Korean Institute of Communications and Information Sciences, the TPC Chair for IEEE VTC-Spring 2014, the General Chair of JCCI 2015. He is Co-EIC of the *Journal of Communications and Networks* and an Editor of IEEE NETWORK MAGAZINE. He was on the editorial board of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He is a member of the National Academy of Engineering of Korea.