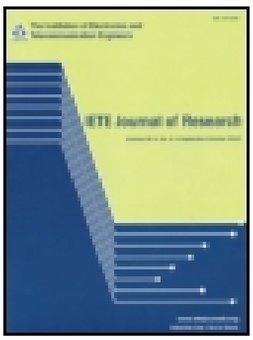

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Cloud-based Battery Replacement Scheme for Smart Electric Bus System

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ABSTRACT

This paper proposes a Smart Electric Bus (e-Bus) Battery SUbstitution Scheme called SBUS in a cloud-based e-Bus system for the efficient battery replacement during e-Bus services. A smart e-Bus system using cloud-based management is considered as an alternative public transportation system. The battery of an e-Bus often needs to replaced, which can be one of the reasons for vehicle traffic congestion. When the battery of an e-Bus was not enough to run itself on its service route, it needs to replace its battery during the running. By this reason, road traffic congestion can be caused by this routine battery exchange. In order to solve this problem, SBUS is proposed to reduce road traffic congestion. To our knowledge, this paper presents the first attempt to investigate how to effectively assign an appropriate e-Bus station for battery replacement e-Bus station for battery replacement to each e-Bus to reduce road traffic congestion. As a result, the proposed scheme can assign an appropriate e-Bus station for battery replacement to each e-Bus to reduce road traffic congestion. To show the effectiveness of the proposed SBUS, we compare it with baseline schemes through simulation. The results of the experiment show that SBUS is more efficient than the baseline schemes in terms of the shorter average waiting time for battery replacement and the shorter end-to-end travel delay for e-Bus services.

KEYWORDS

Battery replacement; Quick battery changing machine; Road-side unit; Smart e-bus; Traffic control center; Vehicular networks

1. INTRODUCTION

Recently, Smart electric Bus (e-Bus) Systems have been actively developed as an alternative transportation system to reduce the dependency on fossil fuels [1–5]. Also, Vehicular Ad Hoc Networks (VANET) have been researched and developed for driving safety and efficiency. This VANET is constructed by vehicles equipped with Dedicated Short-Range Communications (DSRC) [6] in road networks. This DSRC technology has been standardized as IEEE 802.11p, which is optimized for vehicular networks. Also, Global Positioning System (GPS) devices are used through a smartphone and a dedicated navigation device. With these two trends, a natural research question is how to use vehicular networks to efficiently support the operations of the Smart e-Bus Systems via clouds.

Among the operations of the Smart e-Bus Systems, this paper focuses on the battery replacement of e-Buses during their services, considering the waiting time at e-Bus stations for battery replacement. Thus, we define a new optimization problem to minimize the waiting time at e-Bus stations and propose a greedy algorithm called the Smart e-Bus Battery SUbstitution Scheme (SBUS). This algorithm utilizes trajectories (*i.e.*, travel routes) and time (*i.e.*, arrival time and departure time) for e-Bus stations, and this information is maintained by a cloud-based management system called the Traffic Control Center (TCC). TCC can estimate the waiting time for each e-Bus station to replace the battery. Based on the waiting time, TCC allocates an optimal battery-replacement station to each e-Bus by considering the waiting time in each station. Therefore, we can substitute the battery of e-Bus efficiently. Note that this paper is the enhanced version of our previous paper [7].

The remainder of the paper is constructed as follows. Section 2 explains the related work with regard to electronic buses. Section 3 describes a problem formulation for e-Bus battery replacement. Section 4 explains the travel time prediction of e-Buses. Section 5 describes the design for our smart e-Bus battery replacement scheme called SBUS. Section 6 evaluates the performance of SBUS with two baseline schemes. Section 7 shows the applicability of our SBUS algorithm to other domains. Finally, Section 8 concludes the paper along with future work.

2. RELATED WORK

Recently, because of concerns about the environment and limited fossil fuels, Smart e-Bus Systems have

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been actively developed as an alternative transportation system. These smart e-Buses have to recharge or replace drained in-use batteries during their bus service. However, recharging the battery of an e-Bus is inappropriate during its service because battery recharging takes a much longer time than battery replacement [1–5]. Thus, the battery replacement scheme has been preferred in many countries (*e.g.*, South Korea [1–3], China [8], Japan [9], Sweden [10], and Germany [11]).

In South Korea, both battery recharging and replacement methods have been developed. However, because battery recharging takes a long time, battery replacement methods are actively researched. In Pohang city, to solve the limited battery capacity during bus operation, quick battery changing machine (QCM), as a special bus station for battery replacement, has been actively researched. In this city, e-Buses have already been operated by replacing the used battery with a completely recharged one during their bus service [1–3].

In China, one e-Bus system was developed by the Aleees company [8]. This Aleees company is developing battery replacement systems instead of battery recharging systems. The battery replacement systems enable e-Buses to replace the battery for operation without affecting the operation time.

The Japanese government demonstrated that the battery replacement scheme could be effective for use in electric vehicles [9]. Through these battery replacement systems, Japan is developing its own e-Bus systems.

In Sweden, Volvo as one of the world-leading bus manufacturers is developing a next-generation bus, which is an electric vehicle to reduce the emission of carbon dioxide and the operation cost [10].

In Germany, Mercedes-Benz as a leading automotive company is developing an electric version of its long-running city bus to reduce the emission of carbon dioxide. Recently, this company is contracting with a dozen cities to make their buses be completely electric by 2030 [11].

Therefore, the previous studies on battery replacement [1–3] are not about where to replace the battery, but only how to replace the battery. On the other hand, to the best of our knowledge, our paper is the first attempt to investigate an e-Bus battery replacement scheme called SBUS for efficient e-Bus operations. Our SBUS scheme aims at the effective selection of an appropriate e-Bus station for battery replacement for each e-Bus to reduce road traffic congestion, leading to the reduction of road travel time.

3. PROBLEM FORMULATION

In this section, we present the goal, assumptions, and formulation for e-Bus battery replacement in Smart e-Bus Systems. Given trajectories of e-Buses in a target road network, our goal is to determine a battery substitution station for each e-Bus to minimize the average waiting time for all bus passengers at the station.

3.1. Smart e-Bus Systems and Assumptions

In this subsection, we describe the architecture of Smart e-Bus Systems and also assumptions. The following defines the system nodes for Smart e-Bus Systems:

- **Electric Bus (e-Bus):** e-Bus is an electric bus running via the replaceable battery that is installed on the top of the e-Bus [1–3].
- **Quick battery changing machine (QCM):** As shown in Figure 1, QCM is a bus station that replaces a used battery with a fully charged battery for e-Buses [1–3].
- **Traffic control center (TCC**): TCC is a cloud-based management system that collects the statuses of e-Buses and QCMs [12]. Also, TCC collects vehicular traffic statistics, such as (i) average vehicle speed and arrival rate for each road segment at each intersection, (ii) vehicle branching delay and branching probability from one road segment to another road segment, and (iii) travel time from one e-Bus station to another e-Bus station. The TCC schedules the battery replacement time and QCM station to each e-Bus, considering the Quality of Experience (QoE) of passengers, such as waiting time for battery replacement.
- **Road-side unit (RSU):** RSU is a gateway between the wired network and the vehicular ad hoc network [13]. RSU has a DSRC wireless interface to communicate with mobile vehicles and an Ethernet interface to communicate with other RSUs and TCC. As a gateway, an RSU allows vehicles to communicate with TCC via itself. RSUs collect vehicular traffic statistics from passing vehicles and report them to TCC.

The following assumptions are made for SBUS:

- TCC, RSUs, and e-Buses are equipped with GPS navigation systems.
- QCMs, RSUs, and e-Buses are equipped with a device for wireless communications in vehicular networks.
- e-Buses can communicate with TCC to periodically report their mobility information (*e.g.*, position,

Figure 1: Quick battery changing machine [2]

trajectory, direction, and speed) to TCC, and obtain the up-to-date schedule information for battery replacement from TCC. This communication is possible by either DSRC [6] via RSU or 4G-LTE [14] via Evolved Node B (eNodeB).

- Each e-Bus needs only one battery replacement to cover its service route. Most service routes have about 60 km and one fully charged battery allows an e-Bus to run up to 40 km in road networks [5].
- QCMs have enough batteries for the battery replacement of e-Buses.

3.2. Time Complexity of e-Bus Assignment Problem for QCMs

In our paper, to decide which QCMs e-Buses use for the battery replacement, TCC collects the traffic statistics information of e-Buses and the positional information of QCMs, and then calculates the estimated waiting time of each e-Bus at QCMs. With this calculated waiting time for each e-Bus, TCC assigns each e-Bus to a QCM with the estimated locally minimum waiting time. As shown in Figure 2, if it considers the globally minimum waiting time considering all e-Buses rather than the locally minimum waiting time of each e-Bus, an exhaustive search algorithm has exponential time complexity because the time complexity of the algorithm is k^n (*i.e.*, k is the average number of QCMs per e-Bus route and n is the number of e-Buses). Therefore, we cannot use this exhaustive search algorithm for globally minimum waiting time, so we will propose a heuristic algorithm in this paper.

4. TRAVEL TIME PREDICTION

In this section, we model the travel time on both a road segment and an End-to-End (E2E) travel path (*i.e.*, e-Bus trajectory) along the service route of an e-Bus. Note that this paper uses the travel time modeling described in our previous work [15].

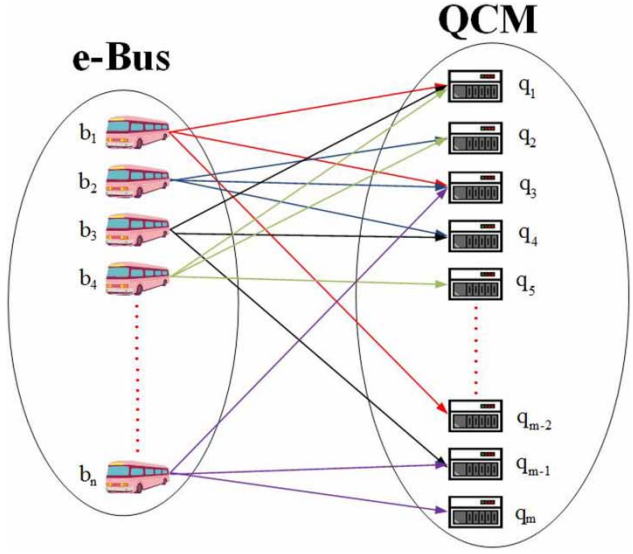


Figure 2: The assignment of e-Bus to QCM for battery replacement

4.1. Travel Time through Road Segment

Let $G = (V_G, E_G)$ be a road network graph, where V is a set of intersections and E is a set of directed road segments. It has been proven that the travel time of one vehicle over a fixed distance in light-traffic vehicular networks follows a Gamma distribution [15,16]. Thus, the travel time through a road segment i in the road network is defined as the link travel delay d_i such that $d_i \sim \Gamma(k_i, \theta_i)$, where k_i is a shape parameter and θ_i is a scale parameter. Note that $d_i \sim \Gamma(\alpha_i, \beta_i)$ where α $(= k_i)$ is a shape parameter and β $(= 1/\theta_i)$ is an inverse scale parameter [17]. To calculate the parameters k_i and θ_i, the mean μ_i and the variance σ^2 can be used for the link travel delay [17] on the given road segment $e_i \in E_G$. The traffic statistics of μ_i and σ^2 are available from a commercial navigation service provider (*e.g.*, Garmin [18]).

Let the mean of di be $E[d_i] = \mu_i$ and the variance of d_i be $\mathrm{Var}[d_i] = \sigma_i^2$; the formulas for κ_i and θ_i are as follows:

$$\theta_i = \frac{\mathrm{Var}[d_i]}{E[d_i]} = \frac{\sigma_i^2}{\mu_i}, \tag{1}$$

$$k_i = \frac{E[d_i]}{\theta_i} = \frac{\mu_i^2}{\sigma_i^2}. \tag{2}$$

In addition to the above mathematical model for link delay distribution on a road segment, our SBUS can accommodate empirical measurements for the distribution of link delay. These empirical measurements can be performed via the report of vehicles (passing through the

road segment) to the RSU taking charge of the road segment. Thus, a more accurate link travel delay distribution will allow SBUS to predict the travel time more accurately for QCM allocation for the battery replacement.

4.2. Travel Time on End-to-End Path

The E2E travel delay in a road network can be modeled with the link delay model in Section 4.1 [15]. Given that the link travel delay is modeled as the Gamma distribution of $d_i \sim \Gamma(\alpha_i, \beta_i)$ for road segment i, the E2E travel delay can be modelled with the sum of the Gamma distributions of the link delays. Given a specific traveling path, it is assumed that the link travel delays of different road segments for the path are independent of each other. With this assumption, the mean (or variance) of the E2E travel delay is approximately calculated as the sum of the means (or variances) of the link travel delays for the links along the E2E path. Assuming that the traveling path consists of N road segments, the mean and variance of the E2E travel delay D are computed, respectively, as follows:

$$E[D] = \sum_{i=1}^{N} E[d_i] = \sum_{i=1}^{N} \mu_i, \tag{3}$$

$$\mathrm{Var}[D] = \sum_{i=1}^{N} \mathrm{Var}[d_i] = \sum_{i=1}^{N} \sigma_i^2. \tag{4}$$

With (3) and (4), the E2E travel delay D is approximately modeled as a Gamma distribution as follows: $D \sim \Gamma(K_D, \theta_D)$, where K_D and θ_D are calculated using $E[D]$ and $Var[D]$ by formulas (1) and (2). Note that if a more accurate distribution for the E2E path is available from the measurements or another mathematical model, our SBUS can use this distribution for a more accurate E2E travel time estimation.

We now discuss the relationship between the arrival time (denoted as T_{ak}) of vehicle V_a at a target intersection n_k and the E2E travel delay (denoted as $D_{a,jk}$) from V_a's current position n_j to the target intersection n_k . Let T^* be the current time. Let $T_{a,jk}$ be the arrival time at n_k for vehicle V_a's E2E travel from the current position n_j to the target intersection n_k. The arrival time $T_{a,jk}$ can be modeled as a Gamma distribution using Equations (3) and (4) such that $T_{a,jk} = D_{a,jk} + T^*$. This is because $T_{a,jk}$ is a linear combination of a Gamma random variable $D_{a,jk}$ and a constant value T^*. For simplicity, we denote $T_{a,jk}$ as T_{ak}, where the vehicle V_a's current position is implicitly known by the GPS navigation systems.

4.3. Travel Time from a Station to the Next Station

We can estimate the arrival time of each e-Bus for a station along its traveling path because it has its own route with an expected travel time from one station to the next station. Thus, we need to calculate this travel time. First of all, TCC gathers the samples of the actual travel time from a station to the next station. Then, we calculate the mean and variance of the samples of the travel time for e-Buses. With the mean and variance of the travel time calculated, we can predict the arrival time from the current position to an optimal QCM, as TCC can estimate the travel time from one station to the next station. Thus, if e-Buses need to replace the battery, TCC can select an appropriate QCM for each of them by estimating the arrival time from their current position to an appropriate QCM using the formulas of Sections 4.1 and 4.2.

5. DESIGN OF SMART E-BUS BATTERY SBUS

In this section, we present our design of the SBUS. The goal in SBUS is to assign an appropriate QCM station to each e-Bus for battery replacement to minimize the average waiting time of each e-Bus at its corresponding QCM station selected by a battery replacement algorithm.

5.1. SBUS Service Scenarios

This subsection presents the service scenarios of the e-Bus battery replacement. Figure 3 shows a target road network for Smart e-Bus Services. In this figure, an e-Bus, $eBus_1$, needs to replace its battery at one of the QCMs (*i.e.*, QCM_1, QCM_2, and QCM_5) on its service route. The question is at which QCM $eBus_1$ should replace its battery with the remaining battery energy for further movement, considering the average waiting time of the Smart e-Bus System. In this paper, we measure the waiting time of each e-bus caused by battery replacement. We show two QCM allocation scenarios for eBus battery replacement in Figure 4. In Figure 4(a), $eBus_3$ of Route-2 and $eBus_1$ and $eBus_n$ of Route-1 are trying to replace their battery at QCM_1. Since they arrive at QCM_1 with a short interval, they make a long queue for battery exchange at QCM_1, as shown in Figure 4(a). This long queue may cause $eBus_n$ to take a long stopping time at QCM_1 for the battery replacement. On the other hand, $eBus_1$ and $eBus_3$ will select QCM_2 and QCM_4, respectively, rather than QCM_1 to decrease the queue length at QCM_1. As a result, $eBus_n$ will be waiting with a short stopping time at QCM_1 for the battery exchange. Thus, a smart QCM allocation is required to satisfy the Quality of Experience (QoE), such as waiting time for the battery replacement, of passengers. In this paper, we will propose an algorithm for our SBUS

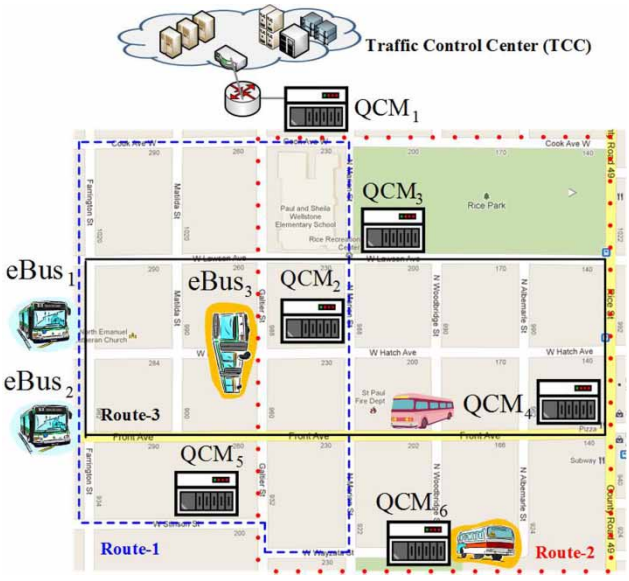


Figure 3: Target road network for smart e-Bus services

and will compare our method with two baseline schemes, described in Section 6.

For QCM allocation, TCC calculates the travel distance that can be covered with the remaining battery energy by each e-Bus and performs an optimization to minimize the sum of the waiting times of all the e-Buses at its corresponding QCM running in a target road network. For each e-Bus, TCC selects a QCM to minimize the e-Bus' waiting time from its current position to the QCM within the reachable distance. We define a wait function w_i for the waiting time of $eBus_i$ where b_i and q_i are the numbers of e-Buses and QCMs on its route, respectively, and $interval_t$ is the inter-departure (*i.e.*, inter-arrival) time of the e-Buses:

$$w_i = f(b_i, q_i, \text{interval}_t), \tag{5}$$

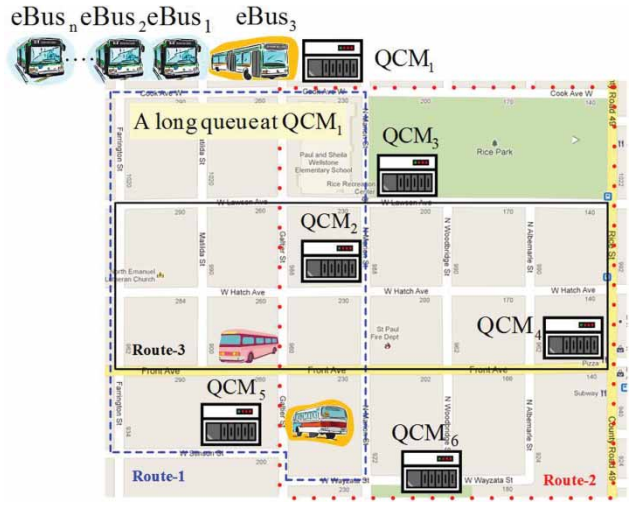
where f is the wait function actually measured by the queueing system for QCM as follows:

$$f(b_i, q_i, \text{interval}_t) \propto \frac{b_i}{\text{interval}_t * q_i}. \tag{6}$$

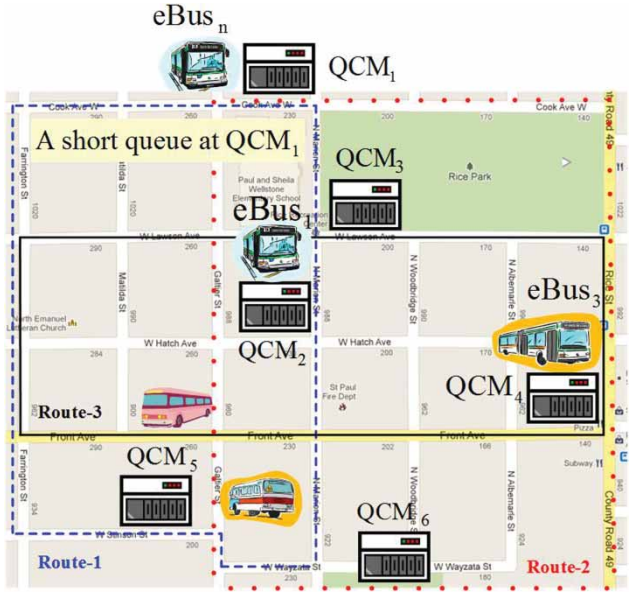
The average waiting time W in the Smart e-Bus System is the sum of all the waiting times of m e-Buses, that is, $eBus_i$ for $i = 1, \ldots, m$.

$$W = \sum_{i=1}^{m} w_i. \tag{7}$$

Our goal is to minimize this average waiting time W, considering the arrival time of e-Buses at QCM stations for the current road traffic conditions.



(a) Bad QCM Allocation that causes a Long Queue at QCM_1



(b) Good QCM Allocation that causes a Short Queue at QCM_1

Figure 4: QCM allocation scenarios for battery replacement (a) Bad QCM allocation that causes a long queue at QCM_1 (b) Good QCM allocation that causes a short queue at QCM_1

5.2. Algorithm for Smart e-Bus Battery Replacement Scheme (SBUS)

In this subsection, we describe a scheduling algorithm for the SBUS to minimize the waiting time of each e-Bus. Note that this algorithm is performed by TCC.

The algorithm of SBUS is specified in Algorithm 1. Let $G = (V, E)$ be a directed graph for a target road network (called a road network graph), where V is a set of intersections and E is a set of directed road segments. Let Q_{all} be the set of QCMs. Let B_{cur} be the e-Bus that needs to replace its battery. It is assumed that TCC has the

Algorithm 1 SBUS Algorithm

1: **Procedure** CONSTRUCT-SBUS(G, $B_{cur,}$ Q_{all})
2: $\mathbf{Q_{reachable}} \leftarrow \emptyset$
3: $\mathbf{Q_{reachable}} \leftarrow$ Extract-Reachable($Q_{all,}$ B_{cur}) ▷ Get QCMs $Q_{reachable}$ which the e-Bus B_{cur} can reach with its redundant battery.
4: $q^* \leftarrow \arg \begin{cases} min \\ qi \in \text{Qreachable} \end{cases} min\ \{q_i + s\}$ ▷ Select the QCM on which the e-Bus B_{cur} whould the least wait for battery exchange service with battery replacement time s.
5: $Q_{sel} \leftarrow Q_{sel} \cup \{q^*\}$
6: *flag* $\leftarrow$ Add($Q_{sel,}$ B_{cur}) ▷ Insert the schedule for the e-Bus B_{cur}into Q_{sel} and assign its QCM to Q_{sel}.
7: **if** *flag* $==$ *true* **then** ▷ Rearrangement is required.
8: *ReConstructSBUS*(Q_{sel}) ▷ Reschedule the e-Buses arriving at the QCM for Q_{sel} after e-Bus q^*.
9: **end if**
10: **end procedure**

schedule information regarding arrival time and departure time of the e-buses for the QCMs. The arrival time is the prediction time of when an e-Bus will arrive at a QCM; the departure time is the predicted time of when an e-Bus will depart from a QCM.

If an e-Bus' battery charging level is less than a predefined threshold, it searches for an appropriate QCM to replace a battery. From line 3 to line 8, the e-Bus B_{cur} is assigned an appropriate QCM, considering the reachable distance and the waiting time for battery exchange. Let us explain in Algorithm 1. In line 3, B_{cur} obtains the list of reachable QCMs $Q_{reachable}$ using its remaining battery energy. In line 4, TCC estimates the waiting time of B_{cur} for each $Q_{reachable}$ by comparing the arrival time and departure time of $Q_{reachable}$. For example, as shown Figure 5(a), TCC has schedule information about the arrival time and departure time for $eBus_1$ and $eBus_2$ for the QCM. The arrival time and departure time for $eBus_1$ are 60 and 100 s, respectively, and those for $eBus_2$ are 110 and 150 s, respectively. If $eBus_3$ arrives at 130 s, $eBus_3$ can replace the battery after the $eBus_2$ departs from the QCM because selected QCM is used by $eBus_2$. Therefore, the waiting time for $eBus_3$ is 20 s (150−130 s = 20 s). By means of this method, TCC estimates the waiting time of the QCMs in $Q_{reachable}$ and allocates the QCM with the shortest waiting time to B_{cur}. In line 6, TCC can add the schedule information for B_{cur} into Q_{sel} and assign this optimal QCM to B_{cur}. From line 7 to line 8, if B_{re} that needed to reschedule the QCM is in Q_{sel}, B_{re} reschedules the optimal QCM to be reallocated.

For example, as shown in Figure 5(b), TCC has schedule information regarding the arrival time and departure time of $eBus_1$, $eBus_2$, and $eBus_3$. The arrival time and departure time for $eBus_1$, $eBus_2$, and $eBus_3$ are 60 and 100 s, 110 and 150 s, and 130 and 190 s (150+ 40 s = 190 s), respectively. However, if $eBus_4$ is expected to arrive at the QCM at 120 s, which is after the schedule of $eBus_3$, the departure time of $eBus_3$ increases by 40 s because $eBus_4$ arrives at the QCM faster than $eBus_3$. Therefore, $eBus_3$ should reallocate the QCM to have a shorter waiting time. This algorithm is complete after TCC has allocated the corresponding QCM to each e-Bus for battery replacement.

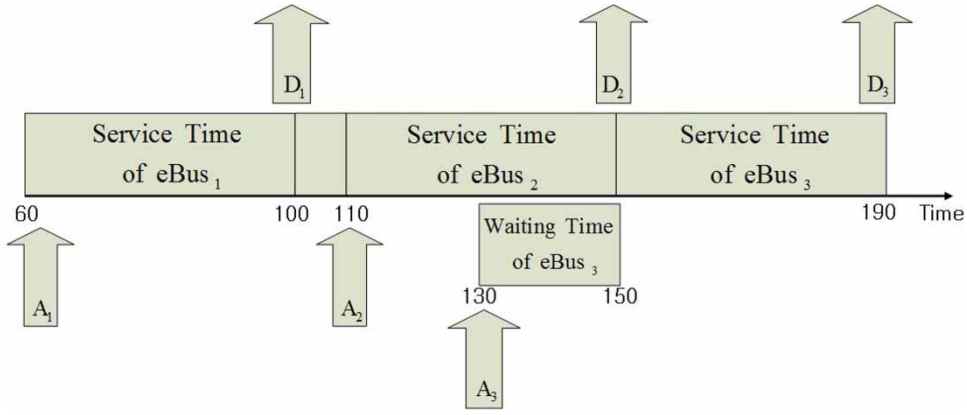
6. PERFORMANCE EVALUATION

In this section, we evaluate the performance of SBUS using the average waiting time of e-Buses. We compare our SBUS algorithm with two baselines algorithms, specifically the Reachable and Random-QCM algorithm (called Random) and Reachable and Farthest-QCM algorithm (called Farthest). The Random scheme randomly allocates QCMs to e-Buses as long as the e-Buses can reach them. The Farthest scheme allocates the farthest QCMs to the e-Buses assuming that the e-Buses can reach them. The other evaluation settings are as follows:

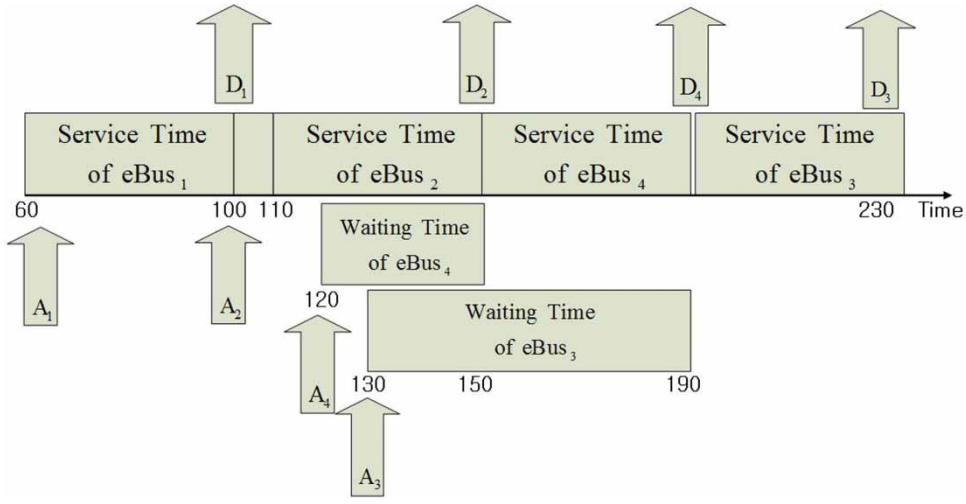
- **Performance Metric:** We use average waiting time as a performance metric.
- **Parameters:** We investigate the impact of (i) the number of e-Buses, (ii) the average number of QCMs per e-Bus route, (iii) the service time interval of e-Buses, and (iv) vehicular density.

We implemented our SBUS and two baseline algorithms on top of a popular mobility simulator called Simulation of Urban MObility (SUMO) – version 0.21.0 [19]. Table 1 shows a simulation configuration to describe the conditions to obtain performance results along with some computational costs. Note that Figure 6 shows a road network of Gwangju City for simulation, which is one of the major cities with an area of 431.05 km^2 in Korea. The road network has 70 QCMs and 50 e-Bus lines for the simulation.

It is assumed that e-Buses communicate with TCC by either DSRC via RSU or 4G-LTE via eNodeB for the communication for their location update and the schedule for battery replacement. Vehicles as background road traffic move from a randomly selected source position to a randomly selected destination position. When they arrive at their destination position, the vehicles randomly select another destination position. On the other hand, e-Buses



(a) The First Schedule Scenario at an Appropriate QCM



(b) The Second Schedule Scenario at an Appropriate QCM

Figure 5: Schedule scenarios for battery replacement at appropriate QCM (a) The first schedule scenario at an appropriate QCM (b) The second schedule scenario at an appropriate QCM

Table 1: Simulation configuration

Parameter	Description
Number of e-Buses	The number of e-Buses moving within the road network. The default of the number of e-Buses is 300.
Number of e-Bus Routes	The number of e-Buses' routes is 50.
Service Time Interval	The service time interval is inter-departure time of e-Buses. The default time interval is 120 s.
Average Length of e-Bus Routes	The average route length of e-Buses is 60 km.
Capacity of Fully Charged Battery	The capacity of fully charged battery is the energy to let an e-Bus run up to 40 km.
Battery Replacing Time	The battery replacing time is 40 s.
Number of QCMs	The number of QCMs is 70 in the road network.
Average Number of QCMs	The average number of QCMs per e-Bus route is 5.
Vehicular Density	The vehicular density is road traffic except e-Buses in terms of the number of vehicles. The default vehicular density is 600.

move according to their own routes. We let the vehicle speed have the normal distribution $N(\mu_v, \sigma_v)$ [20] in the road network for the simulation. The battery replacement time is excluded from the waiting time because the battery replacement time is constant.

Figure 7 shows the road network snapshots for the three battery replacement schemes. As shown in the figure, according to the number of e-Buses, the service time interval, and the vehicular density in the road network, the performance of SBUS obtains better results than the baselines, Random and Farthest. To fairly compare SBUS and the two baselines, we repeated the simulation 10 times and calculated average waiting time with 10 results. The results of the simulations have 95% confidence interval for each case.

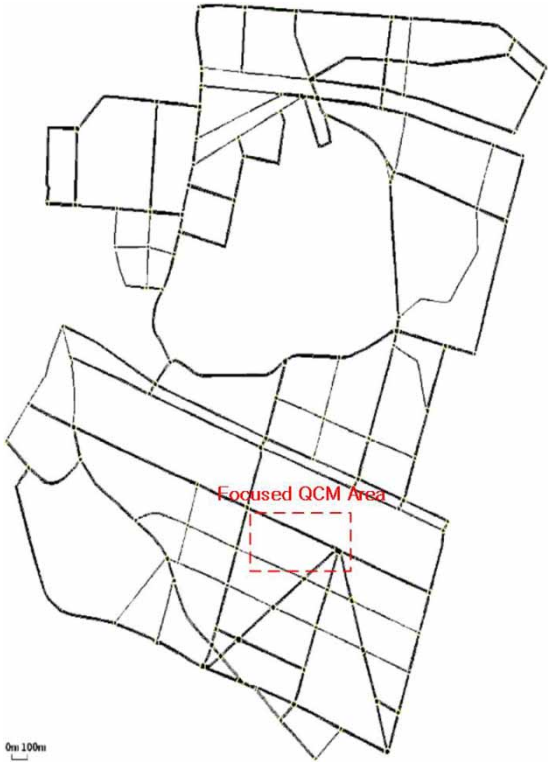


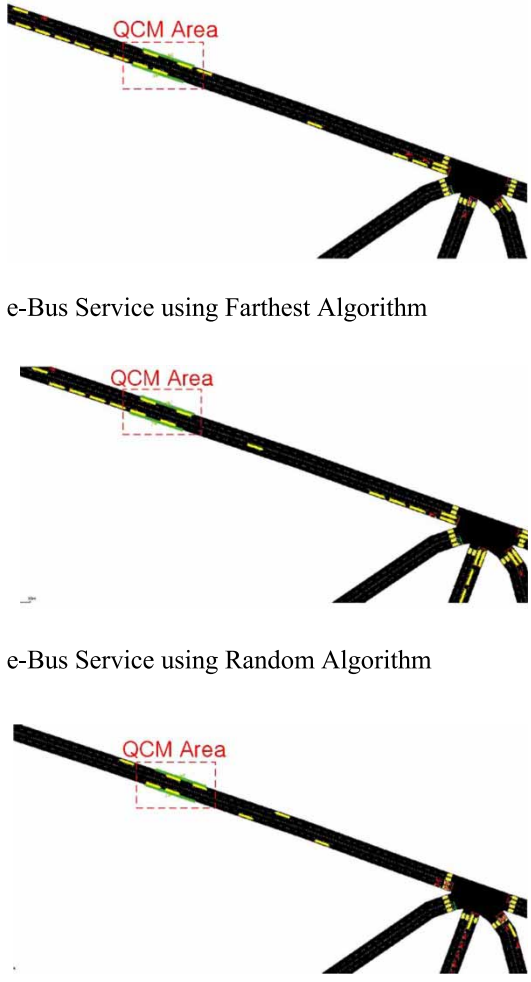
Figure 6: Road network in Gwangju city for simulation

6.1. Behavior Comparison of Battery Replacement Schemes

This subsection compares the behaviors of three battery replacement schemes (*e.g.*, Farthest, Random, and SBUS). For the behavior comparison, as shown in Figure 8, cumulative distribution functions (CDFs) are used to find the distribution of the battery replacement time of these three schemes. As shown in the figure, the CDF of SBUS increases more quickly than those of the other two baselines, such as Random and Farthest. The CDF of SBUS reaches 1 when the battery replacement time is 360 s. On the other hand, those of Random and Farthest reach 1 when the battery replacement time of Random is 540 s and that of Farthest is 580 s. In other words, the maximum waiting times of SBUS, Random, and Farthest are 360, 540, and 580 s, respectively.

6.2. Impact of the Number of e-Buses

This subsection investigates the impact of the number of e-Buses on the performance. As predicted, the average waiting time of all the three schemes is longer as the number of e-Buses increases. As shown in Figure 9, the average waiting time of e-Buses tends to increase with an increasing number of e-Buses. This is because a larger number of e-Buses need to replace more batteries at the QCMs. The baselines of Random and Farthest can make schedules so that some QCMs may have a long queue of



(a) e-Bus Service using Farthest Algorithm

(b) e-Bus Service using Random Algorithm

(c) e-Bus Service using S-BUS Algorithm

Figure 7: Road network snapshots for three battery replacement schemes (a) e-Bus service using farthest algorithm (b) e-Bus service using random algorithm (c) e-Bus service using S-BUS algorithm

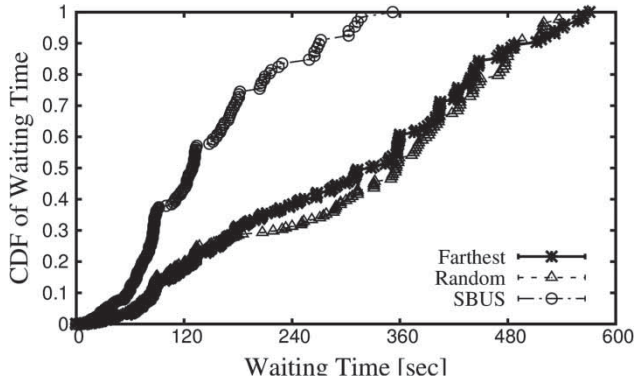


Figure 8: Behavior comparison of battery replacement schemes

e-Buses for battery replacement because they do not perform load balancing well, as shown in Figure 7(a) and 7(b). This long queue of e-Buses leads to a longer waiting time according to the increase in the number of e-Buses.

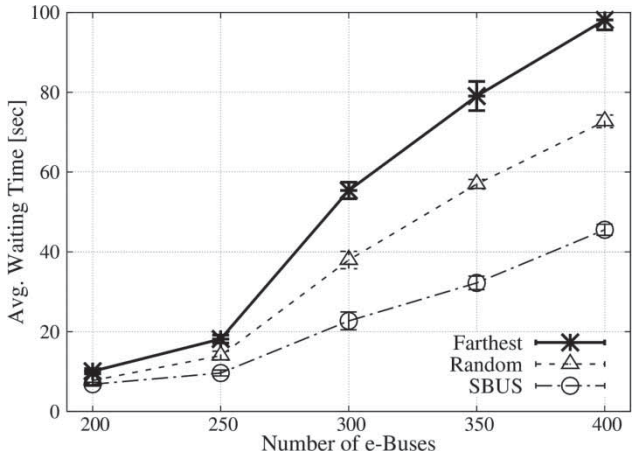


Figure 9: Impact of the number of e-Buses

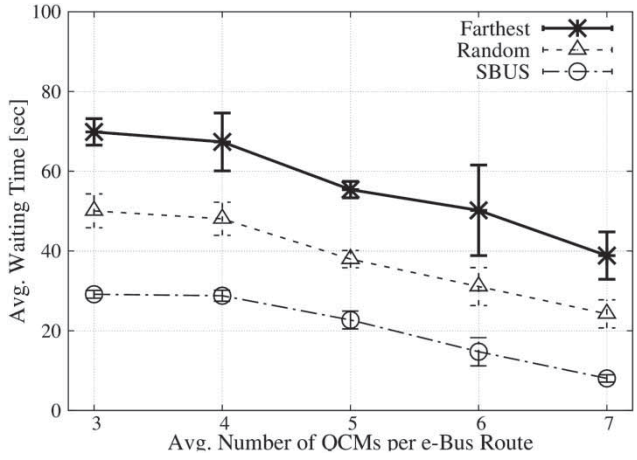


Figure 10: Impact of the average number of QCMs per e-Bus route

6.3. Impact of the Average Number of QCMs per e-Bus Route

This subsection investigates the impact of the average number of QCMs per e-Bus route on the performance. As predicted, the average waiting time of all the three schemes becomes shorter as the average number of QCMs increases per e-Bus route. As shown in Figure 10, the average waiting time of e-Buses tends to decrease with an increasing average number of QCMs per e-Bus route. This is because e-Buses can select QCMs for their battery replacement in a load-balanced way.

6.4. Impact of Service Time Interval

This subsection investigates the impact of the service time interval of e-Buses on the performance. The service time interval is defined as the inter-departure time of two consecutive e-Buses in the same e-Bus route. As the service time interval in the road network increases, the average waiting time of all the three schemes is reduced

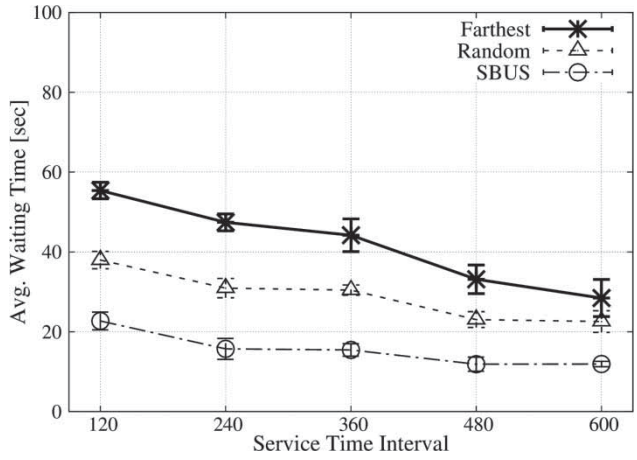


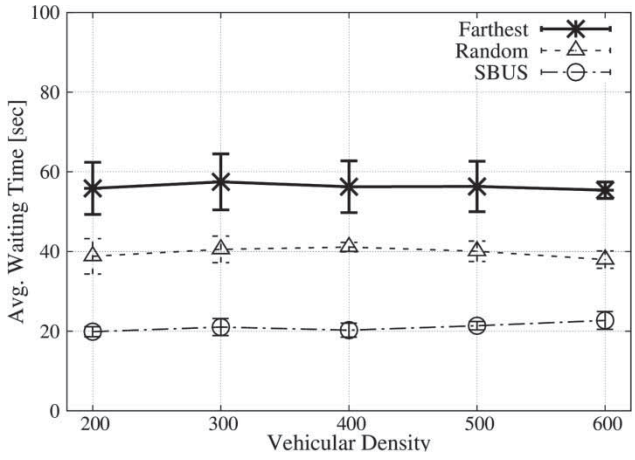
Figure 11: Impact of service time interval

in a similar trend; note that the increase of the service time interval injects a less number of e-Buses into the road network, so this leads to a lower density of e-Buses in the road network.

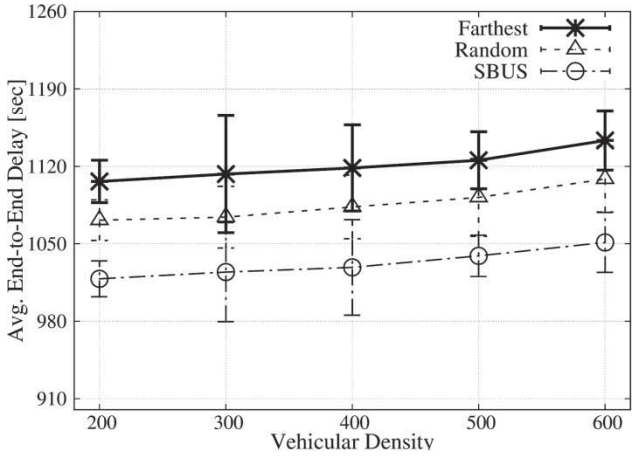
As shown in Figure 11, the average waiting time of e-Buses tends to decrease with an increasing service time interval of e-Buses, that is, a decreasing departure rate of e-Buses. In the figure, SBUS outperforms the other schemes of Farthest and Random because SBUS performs load balancing well for battery replacement at the QCMs. Thus, the average waiting time of SBUS is effectively decreased at the QCM as the service time interval increases.

6.5. Impact of Vehicular Density

This subsection investigates the impact of the vehicular density of the e-Buses on the performance. As shown in Figure 12(a), as the vehicular density in the road network increases, the average waiting time in the SBUS scheme becomes slightly longer, but the average waiting time in the Farthest and Random schemes is not affected much. In Figure 12(a), the average waiting time of e-Buses using the SBUS scheme tends to slightly increase with the increase in vehicular density, but the average waiting time of e-Buses using the Farthest and Random schemes is not influenced by the increase in vehicular density. This is because an increase of vehicular density in the SBUS scheme reduces the accuracy of the predicted time of when the e-Buses will arrive at a QCM for battery replacement. On the contrary, as shown in Figure 12(b), as the vehicular density in the road network increases, the average E2E delay of all the three schemes becomes longer. In Figure 12(b), the average E2E delay of e-Buses tends to increase with the increase in vehicular density. This is because the increase of vehicular density



(a) Average Waiting Time according to Vehicular Density



(b) Average End-to-End Delay according to Vehicular Density

Figure 12: Impact of the vehicular density (a) Average waiting time according to vehicular density (b) Average end-to-end delay according to vehicular density

tends to increase the variation of the passing time of e-Buses in road networks. Thus, the average E2E delay is increased with the increase in vehicular density in the road networks.

Finally, through simulations, it can be concluded that SBUS has the shortest waiting time compared to the other two baselines of Random and Farthest. This is because Farthest and Random do not consider the estimated waiting time due to the queuing of e-Buses for battery replacement. Therefore, SBUS can achieve better performance than Farthest and Random by predicting the waiting time at QCMs for battery replacement.

7. APPLICABILITY OF SBUS ALGORITHM

In this section, we show the applicability of our cloud-based scheduling algorithm called SBUS in addition to e-Bus battery replacement.

7.1. Battery Charging Scheduling of Electric Vehicles

The research on general electric vehicles as well as an electric bus (*i.e.*, e-Bus) have been actively researched to reduce the emission of carbon dioxide and the operation costs [21]. In this case, we should consider that unlike electric buses, electric vehicles have no fixed service routes, having a different route every travel. However, since SBUS algorithm is a cloud-based algorithm, our SBUS algorithm can be applied to the battery charging (or replacing) of general electric vehicles such that they can select appropriate battery charging (or replacing) stations during their operation duration by sharing their travel routes with a central cloud server for our battery charging (or replacing) scheduling.

7.2. Battery Charging Scheduling of Drones

The research for a drone has been spotlighted to facilitate various delivery services for the industry [22] or various aerial missions (*e.g.*, surveillance and tracking) in the military [23,24]. However, the battery capacity for a drone operational time is becoming an important issue because its battery has too short running time and needs long charging time for long-distance drone services [22]. To solve this problem, it is essential to charge (or replace) the battery of a drone at a battery charging (or replacing) station for executing various long-distance drone services.

Our SBUS algorithm can be applied to the battery charging (or replacing) of drones. For various services and missions, many drones will densely fly in the sky. To prevent those drones from colliding with each other, drones need to follow sky routes like airplanes. In this case, where drones have their sky routes (*i.e.*, trajectories), our SBUS algorithm can be applied to the battery replacement or recharging for drones. Therefore, the drones can select their appropriate battery charging (or replacing) stations during their operation duration by sharing their aerial trajectories with a central cloud server for our battery charging (or replacing) scheduling.

7.3. Battery Charging Scheduling with Multiple Chargers

In the case of battery charging scheduling of electric vehicles and drones, it is possible to have multiple chargers at a QCM station to effectively charge the multiple batteries of the electric vehicles and drones at the same time. In a given setting where QCM stations have multiple chargers, our SBUS algorithm can be extended such

that each charger is treated at a virtual QCM station belonging to a physical QCM station having multiple virtual QCMs. With this concept of virtual QCMs in our SBUS algorithm as described in Algorithm 1 in Section 5.2, the electric vehicles and drones can select a virtual QCM to provide the shortest waiting time for battery charging.

8. CONCLUSION

In this paper, we proposed our scheduling algorithm called Smart e-Bus Battery Replacement Scheme (SBUS) for efficient battery replacement. Our SBUS algorithm aims to minimize the waiting time for battery replacement at QCM stations. SBUS takes advantage of the trajectories of e-Buses and the reservation information of battery replacement at QCM stations, along with travel time prediction, based on road traffic information. This SBUS algorithm can be used not only in battery replacement, but also for battery recharging. We expect that this SBUS algorithm can be applied to many other areas to solve similar problems, such as battery charging for electronic vehicles. We believe that our SBUS algorithm will improve traffic flow in road networks where e-Bus systems are deployed to save fossil fuels and also improve the atmosphere via the reduction of CO_2 emission. The effectiveness of SBUS is shown through performance comparison with two baseline algorithms, that is, the Random and Farthest algorithms. As future work, we will include the consideration of e-Bus customers' complaint on the delay due to battery replacement at QCM stations. Also, we will study a placement problem of battery replacement or charging stations for electric vehicles or drones.

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