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Energy Borrowing Transmission Scheme Based on D2D Communication for 5G Networks

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ABSTRACT In our paper, we proposed an Energy Borrowing (EB) transmission scheme which is used to conserve the battery life of user equipment (UE), such as a mobile phone. EB is based on device-to-device (D2D) communication and cellular networks, particularly, on out-band D2D (Wi-Fi Direct, IEEE 802.11) and 5G networks. Since D2D offers higher energy efficiency than cellular networks, in this scheme, a UE with low remaining battery power establishes a D2D connection with a nearby UE, and the nearby UE transfers the low remaining battery UE's packets to/from gNB (5G-base station). As nearby UE plays an active role in the low remaining battery UE's connection with gNB. Therefore, we can rephrase that a UE with low battery power is virtually borrowing the battery resources of a nearby UE. This paper introduces the operation protocol and procedure followed by EB with the use of Wi-Fi Direct and 5G networks. Experiments and simulations demonstrate that EB can extend terminal battery lifetime (a valuable characteristic for long-lasting batteries), and it is more effective as compared with the existing scheme that uses only the cellular network.

INDEX TERMS Device-to-device communication (D2D), 5G, Wi-Fi Direct, IEEE 802.11, energy consumption, long-lasting battery, energy borrowing transmission.

I. INTRODUCTION

In recent times, 5G services are being launched in succession, and the future of mobile communications is expected to soon expand beyond the 4G era. The main pillars of the 5G services are Enhanced Mobile Broadband (eMBB), Massive Machine-Type Communications (mMTC), and Ultra-Reliable and Low-Latency Communication (URLLC). These features enable it to be used for various purposes and scenarios, such as 4K video, smart cities, and self-driving cars [1]. Concomitantly, it is expected that the volume of global mobile data traffic will continue to rise, reaching 607 [EB/month] in 2025 and 5,016 [EB/month] in 2030 [2]

One of the major challenges in this next-generation communication is actively resolving points of dissatisfaction among existing users. There remain many complaints about smartphones. Among them, dissatisfaction with battery-life is particularly high, and in the results of the survey [3], over 70% of the users responded that "long-lasting batteries" was the feature they desired in future smartphones. This was also the top user complaint. In the same survey, in response to the survey item "fear of the smartphone battery running out when going out," *i.e.*, leaving their homes, 61.6% had a fear of their smartphone battery running out, confirming a high degree of concern among several users for battery life.

From the user's perspective, battery life is considered important, for 5G and even beyond 5G. Additionally, use cases will expand, and enhanced functionality and performance will be observed. Issues closely related to user dissatisfaction regarding battery life, as described above, are expected to form a key issue.

Various novel efforts are being made to address the aforementioned issue at the market level. For example, Samsung's Galaxy S10, released in 2019, added a feature called wireless power-sharing [4]. This feature is a power supply function that uses wireless power transmission technology to supply power to other devices physically; this is done by placing the other device (or the peripheral) on the smartphone.

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In the energy-lending method proposed in this paper, the battery, with its life to be extended, does not communicate directly with the base station, it rather uses D2D to access a neighboring terminal that communicates with the base station in its stead. Consequently, the energy consumption caused by the communication is limited, thus the operational time of the device's battery can be extended. This method virtually uses the energy/battery resources of the neighboring device. Therefore, the scheme presented in this research is named "Energy borrowing (EB) transmission scheme".

The authors have been researching on green cellular networks, and we have proposed an energy-efficient communication scheme [5]–[7], and [8]. Presently, our proposed method uses D2D communications in cellular networks, and the commonly associated processes were investigated. D2D has been actively discussed and researched; it is expected to have positive impacts on issues such as coverage enhancement [9], throughput improvement [10], [11] and [12], frequency efficiency [13], and energy efficiency [14]. Similarly, the 3rd Generation Partnership Project's (3GPP) released 12 standardized technical specifications of the Proximity Service (ProSe) that discovers nearby user devices on an LTE network and direct communication between devices [15], [16].

Moreover, D2D is expected to serve as a means of communication when a base station or conventional network becomes unusable during disasters because of a present inability for devices to function without the use of a base station or core network. Research into communication using D2D as a form of information infrastructure during disasters is gaining weight [17]–[20].

As stated above, D2D has various applications, and is also expected to have effects on energy efficiency [21], [22], and [23]. These papers describe how D2D communication is more energy-efficient than cellular communications using a base station. In [24] and [25], the D2D protocol is designed for a scenario involving a cluster using Wi-Fi Direct. Reference [26] implements and demonstrates multi-hop communication using Wi-Fi. In addition, this research validates the energy efficiency and throughput when using D2D. Reference [27] compares energy efficiency when using Wi-Fi and LTE for video streaming. Similarly, various studies of active communication methods for out-band D2D using Wi-Fi are being conducted [28], [29]. In addition, various studies have been proposed to increase energy efficiency through power control, access control, channel allocation control, and relay selection methods [30], [31], and [32].

Traditionally, in the field of D2D research, the purpose is to extend the communication distance, coverage area. Also, there has been much research on power efficiency in D2D field. However, the main purpose of these studies is to improve the overall power efficiency system-wide or even the power efficiency of individual devices, and these studies are not focused on improving user experience from the user's perspective. In contrast, this paper proposes a method to extend the battery life by virtually borrowing power from nearby users, despite communication with the eNB being possible only when the battery is insufficient from the user's perspective.

The challenges and contributions of this paper are follows;

- Address the issue of battery operating times for the individual user, which is a major challenge in recent years, this paper offers a novel concept and scheme for virtual leasing of battery resources by D2D.
- And that this can be a potential approach for resolving dissatisfaction with batteries of users.
- In the experimental part, we analyze the power consumption and download speed of LTE and D2D.
- In the simulation part, the evaluation is based on a specific use case: the number of minutes a user can use a smartphone in a real environment using the experimental results.
- As mentioned above, the originally and novelty are the approach that focuses on the individual the user experience by virtual leasing of battery resources by D2D.

The rest of this paper is organized as follows: Section II introduces the flow and procedure of our scheme; subsequently; in Section III, energy consumption is compared to D2D and cellular communication by analysis, based on the measurement experiment with anechoic chamber, and this section introduces the model of the energy consumption on our scheme; Section IV presents the results of field experiments, in Section V, the performance of the present scheme is tested through simulation using the experimental results; thereafter, the performance of the battery-life extending effect of our scheme is evaluated through the simulation results; lastly, Section VI concludes this article.

II. OVERVIEW AND PROCEDURE OF THE ENERGY BORROWING TRANSMISSION SCHEME

First, this paper presents an overview of EB and its usage scenario. Fig. 1 shows an overview of the scheme. UE 1's remaining battery level is low, its energy consumption must be reduced to prolong operation. EB instructs UE 1 to send a request for cooperation to UE 2 using D2D. Upon receiving the request and accepting it, UE 2 transmits UE 1's packets to/from gNB (the 5G base station).

In general, D2D transmission consumes less energy than cellular network communication. By using UE 2, UE 1 can conserve energy and extend its battery runtime. Moreover, the telecom operator provides UE 2 with an economic incentive for participating in EB, thus both UE 1 and UE 2 benefit. About the basic idea that operators will give economic incentive (e.g. providing points) to L-UE users who cooperate with energy borrowing. This is a reward from the operator for contributing to user satisfaction and quality improvement. The lender gets incentive and the borrower improves the quality; therefore, the operator can improve the service and satisfaction of the users. Users who cooperate in energy borrowing can be identified by the operator through the core network system.

In this study, UE 1 is called the Energy Borrowing UE (B-UE), whereas UE 2 is called the Energy Lending UE (L-UE). The procedure and protocol of our scheme, based on [24] and [25], incorporate D2D communication, designed using Wi-Fi Direct.

In the field of Wi-Fi, much research is being conducted on radio resource management to reduce interference when there is a high density of users [33], [34], and [35]. In addition, much research has been conducted on Wi-Fi/LTE-U coexistence. [36]. Furthermore, Wi-Fi6 uses OFDMA (Orthogonal frequency-division multiple access), which is even more robust to congestion and has improved performance for simultaneous mass connections [37]. Therefore, we decided that Wi-Fi is the best choice for our proposed scheme. Another reason for choosing Wi-Fi is that it is currently the standard for many electronic devices such as PCs and smartphones. Several contemporary users have devices that use a hybrid of 5G and LTE and Wi-Fi. Although there are other methods, such as Bluetooth and Zigbee, we decided that Wi-Fi is the most suitable among the widely used methods because it can satisfy both the speed and energy consumption requirements of a smartphone.

A. FLOW OF THE ENERGY BORROWING TRANSMISSION SCHEME IN 5G

The flow of the proposed scheme is explained below, regarding Fig. 1 and Fig. 2. Fig. 2 shows the sequence diagram for the scheme. In our scheme, L-UE executes EB when its remaining battery, and its 5G connection are sufficient.

1) First, owing to its low remaining battery capacity, UE 1 is required to reduce its energy consumption, and therefore, it activates the "Energy Borrowing Transmission" mode. UE 1 sets its connection state to RRC (Radio Resource Control) inactive mode for 5G cellular networks [38]. This process enables UE 1 to change into the standby mode on 5G, thus saving energy and battery resources. (UE1 called B-UE hereafter.)
2) If the communication request in the B-UE is received, B-UE activates Wi-Fi for a nearby cooperating UE using D2D. B-UE then broadcasts a cooperation request.
3) UE 2 is a cooperating UE, and therefore, UE 2 (called L-UE hereafter) detects B-UE.
4) B-UE establishes a D2D connection with L-UE using Wi-Fi.
5) Finally, L-UE transmits the B-UE's packets to/from gNB.

Once B-UE establishes a connection with L-UE, the link is retained, unless the signal level falls under the threshold (by terminal movement or shielding by movement of surrounding objects) or if no communication request is received within a fixed period. If the D2D link is broken but B-UE traffic has not been completely sent, B-UE restarts the search for a cooperating UE. If B-UE traffic is quiescent with a fixed time, the search process and Wi-Fi operation is terminated to save energy. B-UE continues in RRC inactive mode, hence B-UE saves energy and battery.

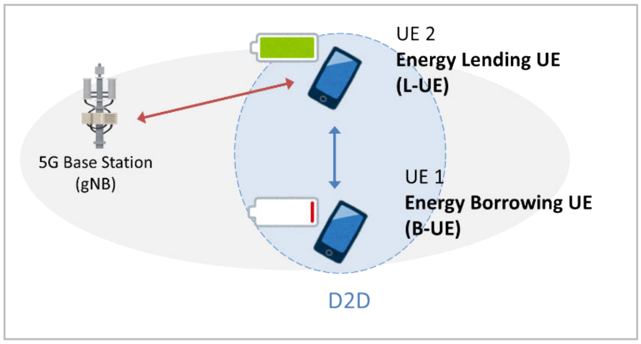

FIGURE 1. Overview of the energy borrowing transmission scheme.

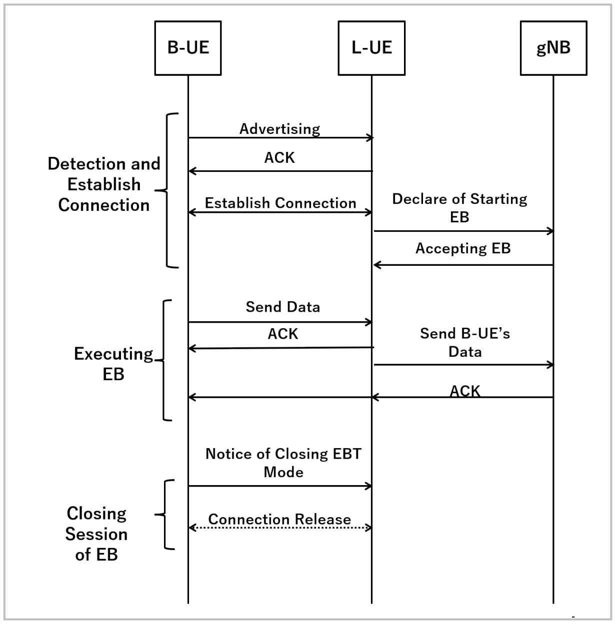

FIGURE 2. Sequence diagram of EB.

B. PROTOCOL AND PROCEDURE OF THE ENERGY BORROWING TRANSMISSION SCHEME

Fig. 3 shows the procedures as the sequence diagram. This proposed protocol is considered based on [24].

1) SEARCH AND DISCOVERY

B-UE sends a probe request for nearby UEs (active scan). L-UE candidates listen to social channels (passive scan). When L-UE receives a probe request, it sends the "Notification of L-UE candidate" response. This notification contains the following information: (1) Channel Quality Indication (CQI), with a value from 0 to 15; (2) Battery resource remaining information (%). B-UE obtains states of all L-UE candidates. In Fig. 3, L-UE candidates are UE 2 and 3.

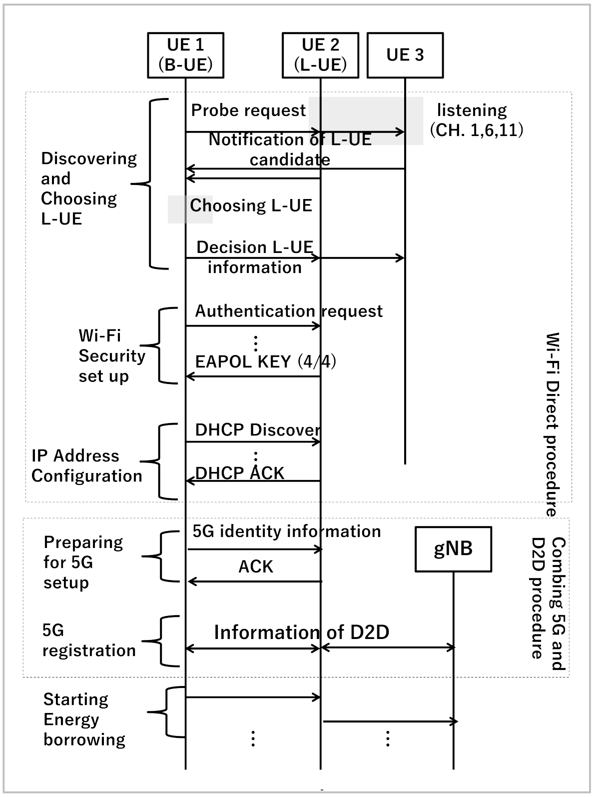

FIGURE 3. Procedure for Wi-Fi direct and 5G in EB.

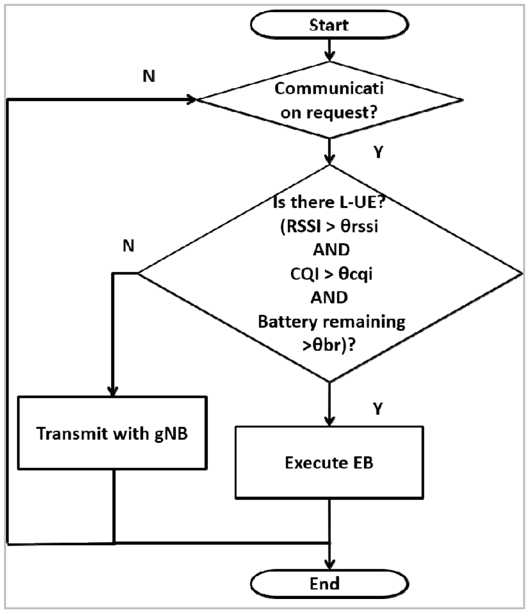

FIGURE 4. Flowchart of B-UE operation in EB.

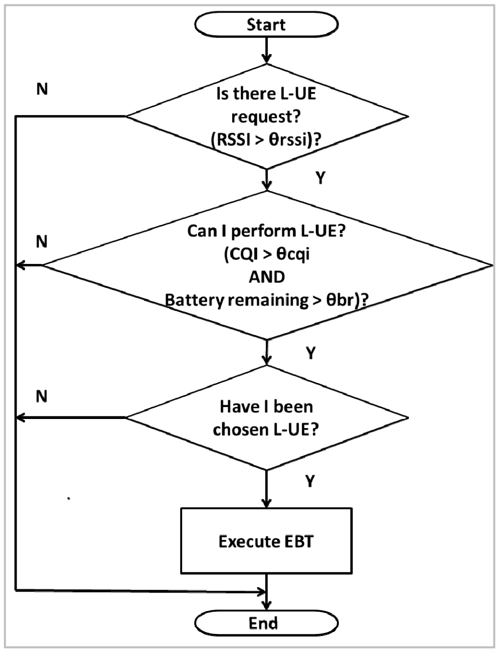

FIGURE 5. Flowchart of L-UE operation in EB.

2) CHOOSING L-UE

B-UE chooses an L-UE from all L-UE candidates. First, prospective devices with CQI and remaining battery levels lower than the threshold are excluded from candidates, given they are unsuitable for L-UE. Moreover, B-UE considers the L-UE with the highest Received Signal Strength Indicator (RSSI) of Wi-Fi. If RSSI with L-UE is strong, B-UE can communicate with low energy consumption. We will show the relationship between RSSI and energy in Section III.

In Fig. 3, UE 2 is selected and becomes L-UE. Next, B-UE sends "Decision L-UE information" to all the L-UE candidates. All the L-UE candidates receive the information and realize which UE was selected as the L-UE amongst all the L-UE candidates.

3) WI-FI SECURITY SETUP

Security is established between the B-UE and the L-UE. The security of D2D communication in cellular communication has been studied in detail, including security structure, functions and requirements. [39], [40] On this basis, this research will use the same method to ensure security as in reference [25].

First, for Wi-Fi, L-UE starts the Wi-Fi security setup with WPS (Wireless Protected Setup). Then, establish the security of Wi-Fi communication.

4) IP ADDRESS CONFIGURATION (DHCP)

L-UE assigns an IP address to B-UE following the Dynamic Host Configuration Protocol (DHCP).

5) PREPARING THE 5G SETUP

B-UE sends L-UE its LTE identity information, which includes its 5G-S-TMSI (5G-STMSI: 5G SAE-Temporary Mobile Subscriber Identity) and C-RNTI (5G C-RNTI: Cell Radio Network Temporary Identifier).

6) 5G REGISTRATION

5G core registers L-UE as a proxy for B-UE, this procedure is followed by the general attachment procedures clause 4.2 in [41], and the core network structure is followed and based on [42]. Also, based on the discussion in [25], [39], and [40], we use the same technique as in [25] to secure

D2D. The eNB sends a Security mode command to the L-UE, and the L-UE forwards it to the B-UE via Wi-Fi. The B-UE sends the response to the security mode command to the L-UE, which sends it back to the eNB. This authentication through the L-UE ensures that it is an energy borrowing pair. This scheme establishes secure communication by using D2D security techniques from existing research.

7) THE START OF ENERGY BORROWING TRANSMISSION

B-UE retrieves mobile services from L-UE. However, if the D2D communication state is low, the B-UE stops using Wi-Fi and uses 5G. Thus, no communication requests are received in B-UE for a period. B-UE disconnects and Turns off the Wi-Fi to save battery while keeping RRC Inactive mode on of 5G.

C. FLOW OF B-UE AND L-UE IN EB

Herein described is how B-UE and L-UE respectively operate in EB. Fig. 4 is a flowchart of B-UE operation in EB. When EB mode is turned on, 5G communication is set to inactive mode. When a communication request occurs, the Wi-Fi is turned on, and an inquiry is made to a nearby device. If there is a device L-UE that satisfies conditions RSSI of D2D > Th_{ssi} (θ_{rssi}), and L-UE's CQI (Channel Quality Indicator) with 5G (θ_{cqi}) > Th_{cqi}, and the battery remaining of L-UE > Th_{rembat} (θ_{rembat}), EB is implemented. RSSI of D2D is used to determine whether B-UE and L-UE can D2D communicate stably with low energy. The CQI of the L-UE is used to confirm whether the L-UE can communicate with the gNB stably. L-UE's Battery remaining information is used to check the battery remaining of L-UE. With these determinations, the B-UE confirms whether the terminal is optimal for L-UE. Moreover, if there is a UE that meets all the conditions, B-UE considers the L-UE with the highest RSSI. If there is no L-UE in the surrounding area, the modem communicates with the base station. Moreover, if there are no new requests for communication within a certain period of time, Wi-Fi is turned off, and no searches are made for nearby devices. Hence, energy consumption is minimized.

In this scheme, the communication quality index for LTE is CQI, and the communication quality index for D2D is designed as RSSI. In other words, CQI is the communication quality indicator between L-UE and eNB, and RSSI is the communication quality indicator of the D2D link between B-UE and L-UE. Therefore, RSSI and CQI are not related. The quality of the D2D link between L-UE and B-UE is not affected by the communication quality between L-UE and eNB (CQI). CQI is only an indicator for selecting the best L-UE. RSSI and CQI are independent communication quality indicators.

Fig. 5 shows the flowchart for L-UE. First, L-UE turns on L-UE mode, subsequently; it turns on Wi-Fi and waits for the EB request. When L-UE receives an EB request from B-UE, L-UE confirms the RSSI of D2D > $Th_{rssi}(\theta_{rssi})$, and other conditions; CQI of 5G, and battery remaining. If all conditions are satisfied that means CQI > $Th_{cqi}(\theta_{cqi})$ AND battery remaining > Th_{rembat} (θ_{rembat}) for exciting EB, L-UE sends the B-UE notification to the L-UE candidate. Hence if an L-UE is selected by the B-UE, L-UE starts EB. When L-UE's CQI, battery remaining, or RSSI is wrong in the EB, it is stopped because it is not suitable for EB.

III. BASIC MEASUREMENT EXPERIMENT

This research has two phases: experiments and simulations. In this section and Section IV, we measured and analyzed the power consumption and download speed of D2D and LTE using a smartphone. Then, in Section V, we used the values from the experimental results in this section to conduct a simulation.

Compared to research that conducts only experiments or only simulations, conducting experiments, and then simulating using the experimental results can provide a more accurate performance evaluation of the proposed scheme. This section will introduce the measurement setup and the experiment details.

A. MEASUREMENT SETUP

Here, the experiment is performed to confirm the amount of energy consumed during data downloading, both on the cellular network and D2D. The cellular network used was LTE (which is the choice of the current mobile system), and as for D2D, Wi-Fi tethering (personal hotspot) was used with IEEE802.11. Furthermore, a commercially available smartphone [43] was used as the experiment device, and the TRYGLE POWER BENCH and the process recorder by TRYGLE [44] were used as the measuring equipment and program respectively. A measurement terminal was set on the positive terminal of the UE's battery. The energy measurement device recorded an electric current (mA) at the measurement terminal. Additionally, a process recording program was installed in the UE. This program recorded the general UE processes (*e.g.*, voltage of the battery, data amount received and sent, CPU utilization, and battery temperature). Therefore, this experimental tool calculates the energy consumption of UE based on an electric current and voltage, and we analyzed the relationship of the energy consumption and data communication on UE. In this experiment, the energy consumption was measured while receiving large amounts of data. This allowed for the analysis of the relationship between the energy consumed by the UE during data transfer over LTE and D2D. Moreover, in order to confirm the trend of energy consumption by the communication state, multiple signal strengths were measured. We reproduced the best communication state for LTE and D2D, and from there, we reproduced the communication condition approximately. The LTE signal intensity was measured with Reference Signal Received power (RSRP) of −60dBm, −74dBm, −84dBm, −96dBm, −105dBm, and −115dBm respectively. In addition, for D2D, a measurement was made by the RSSI. The signal strengths between the master and slave Wi-Fi tethering units were −44dBm, −54dBm, −62dBm, −74dBm, and −84dBm.

The RSRP for LTE gNB of master unit in Wi-Fi tethering was −62dBm.

The measurement procedure is detailed below:

1) For preparation, we uploaded a large dataset in an online storage. The dataset used was a 2.56 GB movie file.
2) We tracked the energy consumption of the smartphone and all the processes while downloading the video file in the (1).

Thus, by measuring the various signal strengths, we were able to analyze and compare the energy consumptions and the amounts of data received for each case.

To measure pure communication energy consumption, we conducted the following experiment. When measuring LTE, only LTE communication was kept active by turning off Wi-Fi. For D2D measurements, we turned off LTE and turned on Wi-Fi. In addition, we stopped all applications running in the background that are irrelevant to our experiments. All conditions, such as screen brightness, were the same. Then, we were ready to measure the power consumption of purely communication. In the case of D2D measurements, the parent and child smartphones were each fixed on a tripod and separated by a distance to reproduce each RSSI. The D2D parent unit, which was connected to the LTE eNB, did not move. Therefore, the quality of the parent unit, RSRP -62dBm, for LTE, was always stable. By moving only the child unit farther away, the D2D reception strength was weakened. This reproduced each RSSI. We attached a measurement equipment to the smartphone of the child device, which was a D2D user, and performed the measurement. In the case of LTE measurements, we moved the smartphone with the measurement equipment from outdoors to inside a room and then inside an anechoic chamber to reproduce each RSRP. By fixing the smartphone device with measurement equipment on a tripod and measuring it while the device was stable, we obtained stable data.

Flow of the experiment; 0 s: Start measurement. 60 s: Start downloading. Tap the download button. 90 s: End of download. Tap the stop download button.

Tapping the download button started the download, but power consumption owing to touching the screen became noise. Therefore, the part of the screen that stabilized after a short time after the tap was the power consumed by pure communication alone. We considered this part and analyzed the communication speed and power. In other words, we analyzed the amount of data that could be acquired per unit of power.

Fig. 6 shows the energy consumption and download speed in D2D −62dBm. The X-axis represents time. And the Y-axis represents the energy consumption (current) and the download speed. We can confirm that the power consumption (red line) has increased since the 1 minute mark. The download speed (blue line) can also be confirmed to have increased from 1 minute as well.

We calculated the amount of data that could be acquired per unit of power using these measurement results.

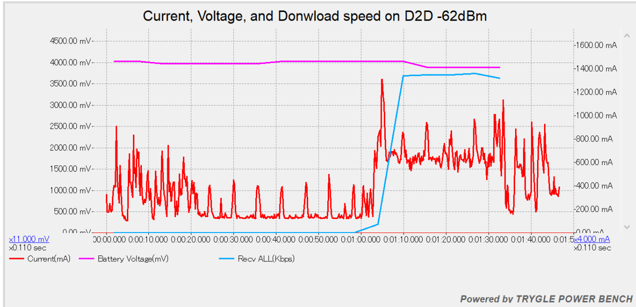

FIGURE 6. Energy consumption and download speed in D2D -62dBm.

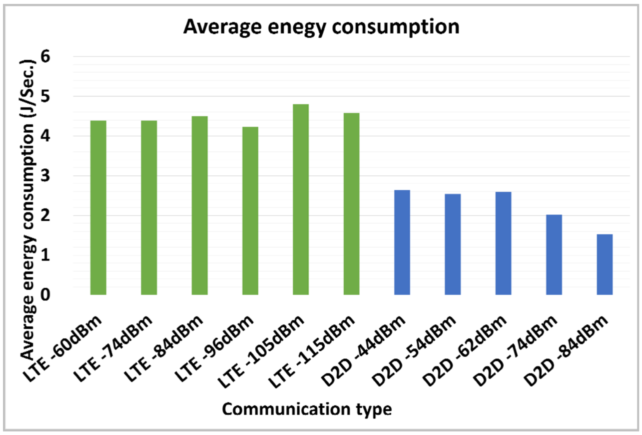

FIGURE 7. Average energy consumption in data downloading on LTE and D2D.

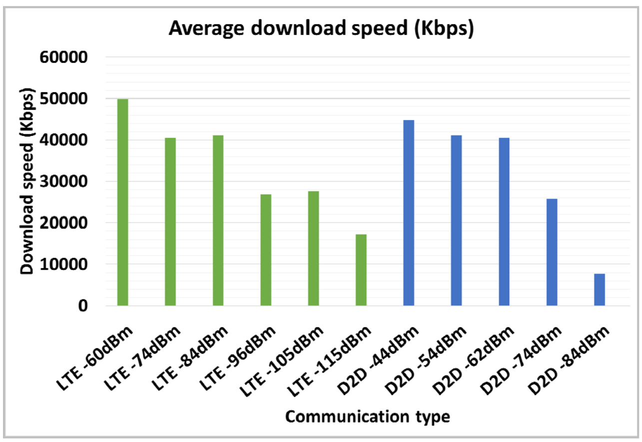

FIGURE 8. Average download speed on LTE and D2D.

B. MEASUREMENT RESULTS

In this section, the experimental results are presented. First, Fig. 7 shows the average energy consumption during data downloading. The Y-axis is the energy consumption J/Sec,, and the green bars show the energy consumption of LTE. The blue bars represent the energy consumption of D2D. It can be seen that all the energy consumption of D2D is smaller than 3J/Sec. From this figure, it is understood that energy consumption is lower when using D2D than when using LTE.

Fig. 8 depicts the average download speed for both D2D and LTE. The RSRP of the base unit for D2D Wi-Fi tethering was −62dBm. It was found that D2D levels of −44dBm, −54dBm, and −62dBm could achieve communication speeds comparable to LTE at −60dBm, 74dBm, and −84dBm.

Fig. 9 is a diagram summarizing the abovementioned results. The X-axis represents the average energy consumption, and the Y-axis represents the average download speed. From this graph, it can be confirmed that the volume of data communication is large when the communication state is good for D2D and LTE, respectively, and the volume of data that can be received becomes smaller with a worse communication state. Concerning energy consumption, in contrast, it was found that for D2D where the communication state deteriorates, a less amount of data is obtained and energy consumption decreases.

Fig. 10 shows the energy when downloading 100 MB of data using D2D and LTE. From this result, it is understood that the communication is made between D2D in the range -44dBm to -74dBm; therefore, communication can be achieved at lower energy consumption when using LTE. The reason is that when Wi-Fi tethering is in the range of 44dBm to -74dBm, the download speed is fast, and the energy consumption is low, thus the total energy consumption is low. However, in the case of D2D at -84dBm, it can be seen that the energy consumption exceeds that of LTE. This can be attributed to the fact that although energy consumption per second is low, the amount of data that can be downloaded is also low and takes more time, resulting in high energy consumption. It can therefore be confirmed that when communicating using a weak D2D signal strength in a poor reception environment, the energy consumption may be higher than that of LTE.

Fig. 11 shows the results of calculating battery operating times when 100 MB is downloaded once every 30 s, when the remaining battery level of the mobile device is 10%. From these results, it can be confirmed that there is a tendency for the battery operating time to be shortened for both LTE and D2D when the reception strength becomes weak, and the communication environment deteriorates. The shortest operating time is 8.9 min at LTE -115dBm and the longest operating time is 40.5 min at D2D -44dBm. Subsequently, we confirmed that D2D can extend the battery up to 4.6 times, and the extension time is 31.6 min. Excluding D2D -84dBm, the use of D2D is expected to have a certain effect on battery life. From the result, the Th_{RSSI} of D2D discussed in Section III can be set to -74dBm as an example in this case.

Figs. 7, 8, and 9 show the raw data of the experiment, and Fig. 10 and 11 show the results of the analysis calculated by combining the results of Figs. 7, 8, and 9. Fig. 7 indicates that -96dBm in LTE consumes less energy than other RSSIs. However, in Fig. 8, we can observe that the download speed of −96dBm is slower and almost the same as -115dBm. This can be explained by the LTE control, which reduced the power consumption at -96 dBm and simultaneously reduced the download speed. Therefore, in terms of energy consumption, which is the raw data in Fig. 7, -96 dBm appears to consume less energy than the other RSSIs.

However, if we analyze this together with the download speed, we can observe that the power consumption required to download data is correlated and shows a consistent trend, as can be noted in Fig. 10. The same applies to −105dBm. According to Fig. 8, the download speed is faster than −96dBm. However, according to Fig. 10, where we calculated and analyzed the download speed and the energy consumption together, it can be noted that the energy consumption and the download speed are correlated and show a consistent trend.

In addition to the analysis of energy consumption, data communication volumes, and battery consumption as mentioned, we conducted an experiment to clarify the extent to which this method can be applied in various environments. For this, the average reception strength was measured using line-of-sight communications between a Wi-Fi-tethering base unit and a handset. Fig. 9 shows the resulting relationship; it is expected that a signal strength, RSSI greater than D2D

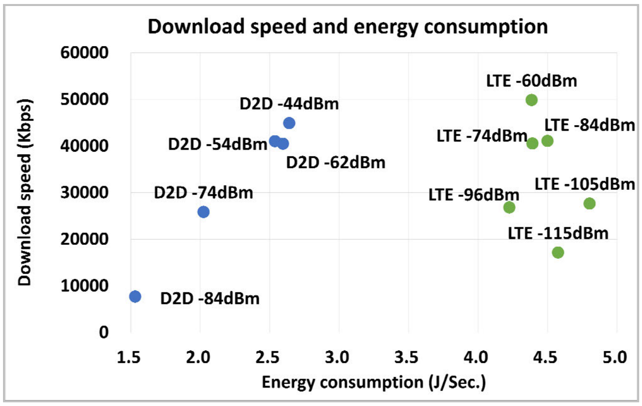

FIGURE 9. Relation for download speed and energy consumption in LTE and D2D.

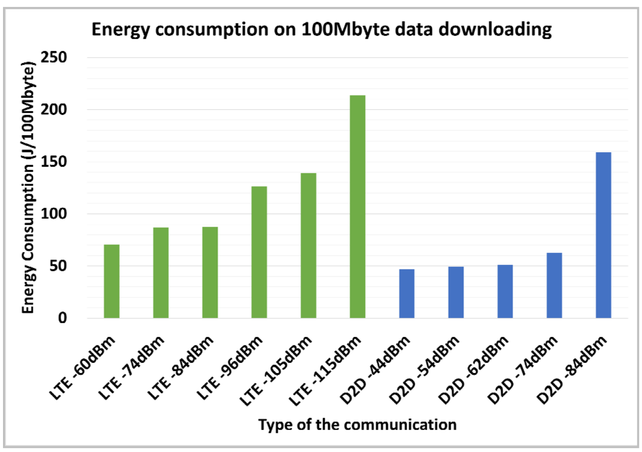

FIGURE 10. The energy when downloading 100 Mbytes of data using D2D and LTE.

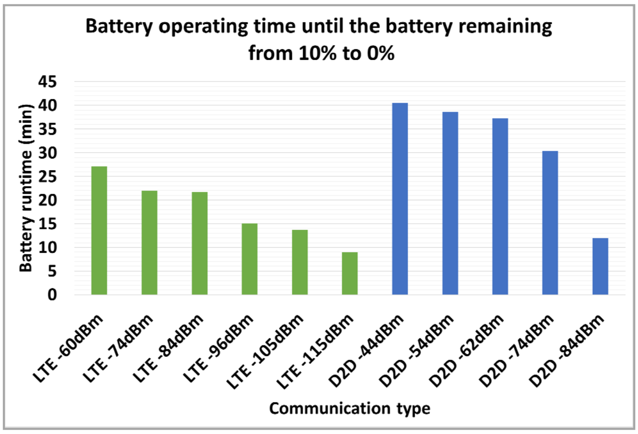

FIGURE 11. **Battery operating time until the battery remaining 10% to 0% (download 100Mbyte every 30 s).**

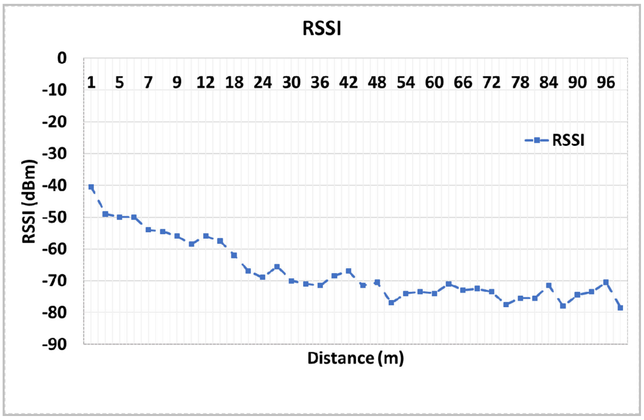

FIGURE 12. **Relation of the distance and RSSI of D2D.**

−74 dBm will lead to an extended battery operation. From Fig. 12, it is observed that at a distance of approximately 50 m, communication cannot be achieved at a signal strength greater than -74dBm. Therefore, it is expected that this method be used in various environments, both indoors and outdoors.

To confirm the effectiveness of our proposed scheme, we verified the energy required for setting up D2D communications. We measured the standby energy of D2D, LTE, and the airplane mode to clarify the energy consumption of the D2D setting up. Fig. 13 shows the results of these measurements. We verified that the energy consumption of LTE is higher than that of D2D and the airplane mode. There was no consistent trend in LTE energy consumption because LTE had a detailed power control. The results of this experiment are only an example for this terminal and operator. However, by comparing D2D and LTE, it was verified that D2D had very low energy consumption. Also, the standby energy consumption of D2D and the airplane mode were almost the same. We noted that the setup energy for D2D was very low. This result indicated that the energy required for the setup of this scheme did not have a significant effect on battery consumption.

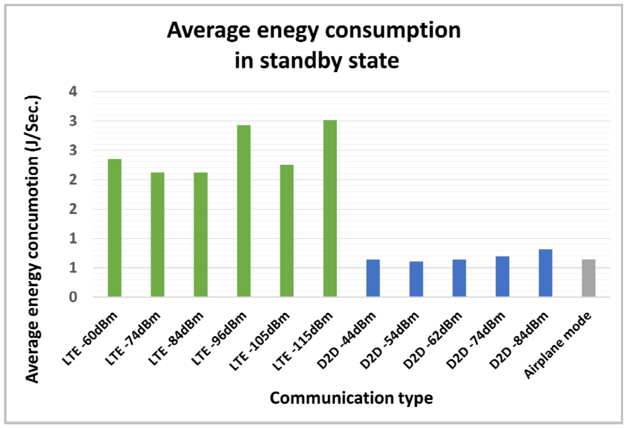

FIGURE 13. **Average energy consumption in standby state.**

C. MODEL OF THE ENERGY CONSUMPTION

We developed the mathematical model for energy consumption on the proposed scheme based on the result of the measurement experiment as shown the Fig.6 and the system model as shown the Fig.2. The parameters are as below and can be shown by the equation 1.

PEB: Probability of execute EB
ECTOT_B-UE: Total energy consumption
β D2D-idle: E nergy consumption of idle of D2D
β5 G-idle: Energy consumption of idle of 5G
V: Voltage
I: Current

$$EC_{\text{total}_{\text{B-UE}}} = P_{EB}\left[\beta_{\text{D2D-idel}} + \left\{\int_{t_{D2D-start}}^{t_{D2D-end}} V(t_{D2D}) \times I(t_{D2D})dt\right\}\right] + (1-P_{EB})\left[\beta_{\text{5G-idle}} + \left\{\int_{t_{5G-start}}^{t_{5G-end}} V\,(t_{5G}) \times I\,(t_{5G})\,dt\right\}\right] \quad (1)$$

IV. FIELD MEASUREMENT EXPERIMENT

The experiments described in the previous sections were conducted in a laboratory with an anechoic chamber for accuracy. The anechoic chamber was also used to verify the relationship between power consumption and reception strength.

In addition, we conducted experiments in several real outdoor environments to see if our scheme was generally effective in multiple scenarios. The experiments were conducted in five locations. The locations of the experiments are shown in Figure 14. In this way, we confirmed the effectiveness of our scheme in various environments. The experimental method was the same as described in Section III, measuring the average power consumption during data download. In the experiment in Section III, we reproduced the reception strength of the base station and D2D by using an anechoic chamber to check the relationship between download speed

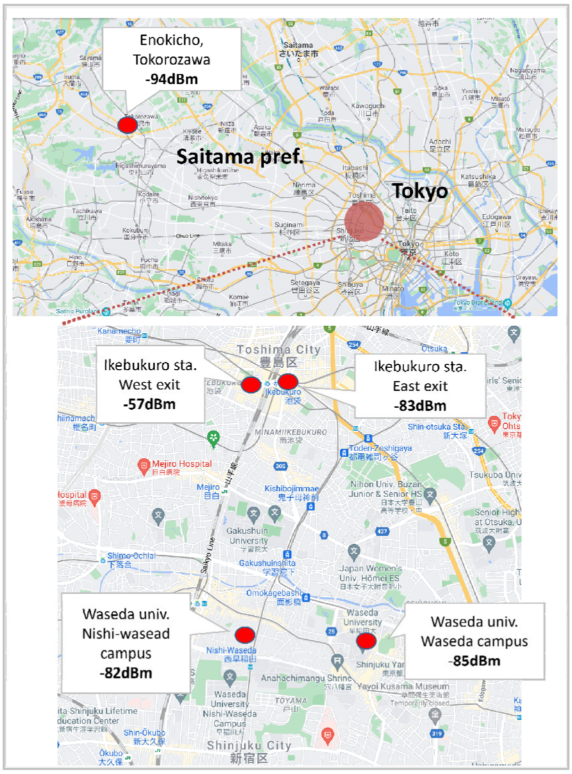

FIGURE 14. Map for the experiment point.

and reception strength. It was found that the lower the reception strength, the lower the download speed and the higher the power consumption. On the other hand, this time we conducted experiments in several outdoor areas. The environment was different in each area: a major station in the city center, a university campus, and a residential area, so the population density and communication traffic were also different. However, from the results, we can confirm the general effectiveness of the proposed method regardless of traffic, population density, city center, or residential area. Figure 15 shows the energy consumption J/Sec. in different areas. It can be seen that the energy consumption of D2D is lower than that of LTE in all locations. At all locations, the Wi-Fi RSSI is -45 dBm.

Figure 16 shows the download speed per second by area. It can be seen that at all points, the communication speed is almost equal between LTE and D2D, and D2D is comparable in download speed. Figure 17 shows the results calculated by analyzing the measurement results in Figures 16 and 17. It shows a comparison of the power consumption J when 100 megabytes are acquired by LTE and D2D in different areas.

From this result, it can be confirmed that power consumption is lower when using D2D in all areas. It was confirmed that D2D consumes less power in various environments such as residential areas, train stations, and university campuses.

From this, it can be understood that this method is generally effective in all scenes. In addition, Figures 18 shows the average J/Sec,, average download speed, and average power consumption when 100 Mbytes are acquired for all locations in Figure 14. These results confirm that D2D generally consumes less power in multiple scenes in real-world environments, such as residential areas and train stations.

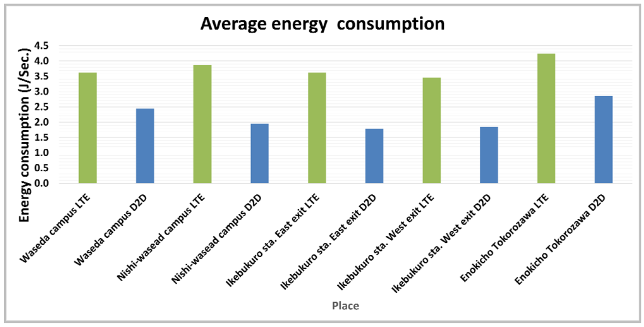

FIGURE 15. Average energy consumption at each location.

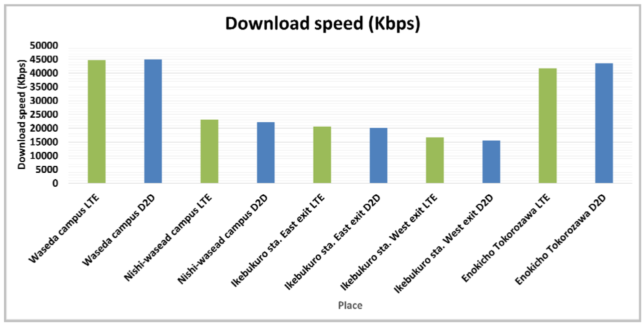

FIGURE 16. Average download speed at each location.

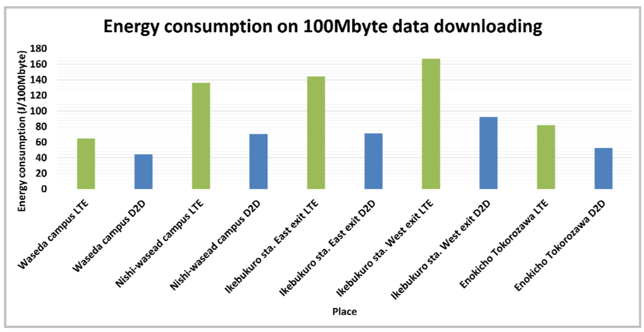

FIGURE 17. Energy consumption on 100Mbyte at each location.

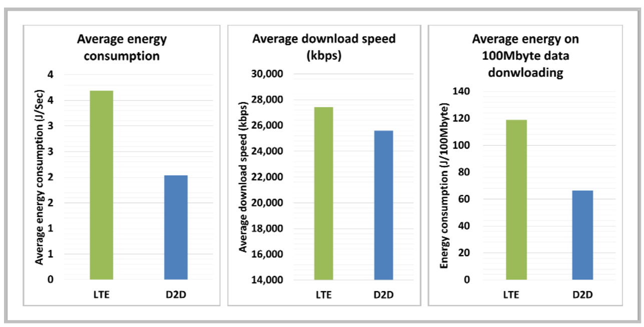

FIGURE 18. The average value of all locations.

V. SIMULATION STUDY

The results and values of the measurement study introduced in Section III were used to verify the performance of the proposed scheme. As mentioned, simulations were used to compare the battery operating time, with and without EB. In this study, we compare the proposed scheme with the LTE scheme that is in practical use. Therefore, we have compared the EB with other schemes in Section V. In addition, this comparison is based on the experimental results obtained in Section III, and we recognize that the results are realistic and concrete. And, Matlab is used for the simulation tool.

A. SIMULATION SCENARIO AND PARAMETERS

First, the simulation scenario is introduced. In this evaluation, passengers on a train are considered as an example of an outside environment. The performance evaluation is executed in a scenario in which train passengers use EB, and they borrow and lend their battery resources among each other. A specific simulation scenario is presented below.

1) First, it is assumed that the environment is contained in a single cabin of the train. In addition, it is assumed that the passenger rate is 50%, and there are 77 passengers, hence 77 UEs. The size of the train has been discussed in [45].
2) It is assumed that the B-UE users, borrowing energy, make up 10% of the total 77 passengers in the carriage. The B-UE's remaining battery is 10%. Moreover, considering the lending, evaluations were made at three rates of the total L-UEs, *i.e.*, 10%, 50%, and 90%. The B-UEs download 100 megabytes of data every 30 s. In the current scenario (without EB), all UEs only transmit using LTE. In the scenario with EB, if a B-UE can find an L-UE with D2D, B-UE establishes a D2D connection, and L-UE transmits B-UE's packets to/from gNB. If the B-UE cannot find any L-UEs, it connects directly to gNB via LTE. Figure 19 depicts the simulation scenario.

We focused on the energy consumption and battery operating time in this research. The total energy consumption of the B-UE in the EB scenario is shown below; $EC_{B-UE-TOT} = EC_{EBTOT} + EC_{LTETOT}$, the total energy consumption of B-UE, $EC_{B-UE-TOT}$ is the sum of the energy consumption EC_{EBTOT} (total energy consumption of EB) and EC_{LTETOT} (total energy consumption of LTE). Additionally, in the simulation, the energy consumption value obtained in the experiment described in Section III is used. Therefore, when 100 megabytes is downloaded in a single instance of communication, energy consumption occurs, as illustrated in Fig. 14, decreasing the charge of the B-UE battery. Moreover, the quality of D2D communication is based on the distance between B-UE and L-UEs, which is indicated by the data obtained from direct measurements, as shown in Fig. 12. In addition, as confirmed in Figure 11, the energy efficiency at −84 dBm is less than that of LTE. Therefore, in this simulation, LTE was chosen for communication environments worse than the threshold value of −74 dBm.

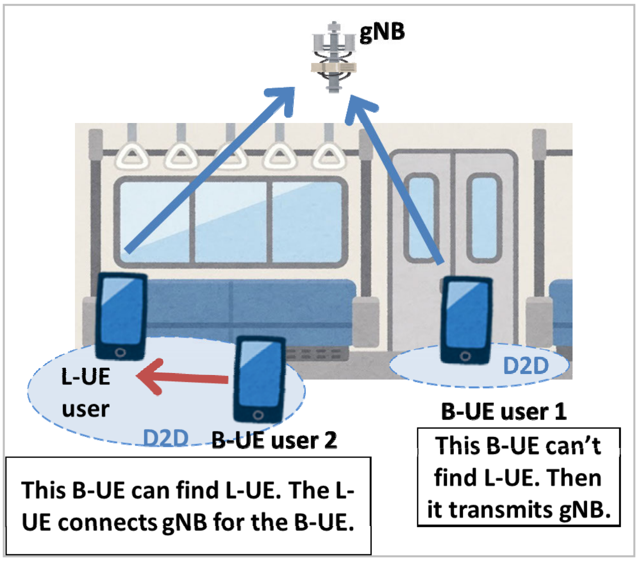

FIGURE 19. Simulation scenario and environment.

Based on this simulation, the following parameters were evaluated: The average battery service time with and without EB, the average extension time by EB, and the extension rate of the battery operating time by EB. We calculated the extended time based on RT_{EB}-RT_{LTE}, the extended time is the difference between the operating time with EB RT_{EB} and the operating time without EB RT_{LTE}, which only uses LTE. The battery extension rate from EB is calculated as follows; the battery extension ratio is $(RT_{EB}/RT_{LTE})*100$.

Table 1 lists the simulation parameters. This table summarizes the simulation environments and scenarios described above. As shown in Table 1, the battery capacity is 2800 mAh under the same conditions as the experimental smartphone in our simulation study.

B. SIMULATION RESULTS

The simulation results are shown in Fig. 20. The figure shows the service operating time of UE without the proposed scheme and extended time by the proposed scheme. The Y-axis represents time in min, and X-axis is the signal strength of LTE, RSRP (dBm). All the black lines show the UE service operating time without EB. The UE uses only LTE. Hence, even if there are L-UEs nearby, the UE does not use EB. Therefore, the same result is always obtained.

lines shown by the proposed scheme, when the LTE connection state is strong, the UE battery conserves life. When the connection state is weak, the energy consumption grows, and the UE consumes more battery. This is shown as the experimental result in Section III. From the black lines in Fig. 20, we can confirm that the UE operating time without EB is 9.3∼28.4 min with each RSRP of LTE. The red line shows the extended time by EB with 10% L-UE in all UEs, the blue line shows the extended time by EB with 50% L-UE, and the green line shows the extended time by EB with 90% L-UE. We can confirm that the EB can extend the UE service operating time at any RSRP of LTE.

TABLE 1. Simulation scenario parameters.

Parameters (scenario)	Value or Explanation
The number of UE	Vehicle occupancy = 50% (77 UE, that means 77 users)
LTE RSRP	-60 dBm, -74 dBm, -84 dBm, -96 dBm, -105 dBm, -115 dBm
LTE RSRP of the L-UE	-62dBm
B-UE ratio (of all UEs)	10%
L-UE ratio (of all UEs)	10, 50, and 90%
The cabinet size of train	20 × 2.85 m
Battery capacity	2800 mAh
Data interval	30 s
Downloaded data size	100 Mbyte
Battery remaining of L-UE (%)	10 %

TABLE 2. The battery extension rate.

	10% L-UE in all users	50% L-UE in all users	90% L-UE in all users
LTE -60dBm	143.8%	147.6 %	148.5 %
LTE -74dBm	176.5%	180.7 %	182.1 %
LTE -84dBm	180.3%	184.8 %	186.0 %
LTE -96dBm	255.3%	263.2 %	264.0 %
LTE -105dBm	283.4%	290.0 %	292.2 %
LTE -115dBm	440.2%	450.2%	456.8%

For example, at -115dBm of LTE, the service operating time of UE without EB is 9.3 min. Contrastingly, if there are 10% L-UE in all users, and the UE uses EB, then B-UE's service operating time is extended by 31.7 min at -115 dBm of LTE. Therefore, B-UE can use its battery for about 41 min with our scheme. Eventually, the extension rate of service operating time is 4.4 times. Additionally, at -115 dBm, the UE service operating time without EB is 9.3 min. If there are 90% L-UE in all users and the UE uses EB, B-UE's service operating time is extended by 33 min, hence the B-UE's operating time is 42.3 min, and the extended rate is 4.56 times.

From the simulation results shown in Fig. 20, we can confirm that if the UE is without EB, the operating time is 9.3∼28.4 min. Conversely, if the UE uses EB, then B-UE's service operating time is about 42 minutes in any condition. The service operating time with EB is the sum of the UE operation time without EB (each black color point in Fig. 15) and extended time with EB (each red, blue, or green color point in Fig.15). We can confirm EB can extend the UE service operating time by any RSRP of LTE and the number of L-UE in all users. This is because EB was shown to be able to find L-UE even in an environment where L-UE is as low as 10% among the passengers. Additionally, EB was able to extend the UE service operating time. As shown in Fig. 12, EB can be used stably when operating up to a distance of approximately 50 m. Therefore, even if the number of L-UEs is small, L-UEs can be found within the D2D communication range. A stable performance is confirmed in this simulation

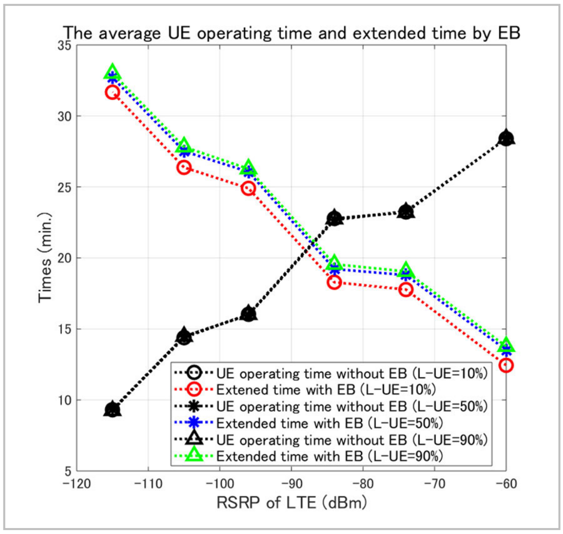

FIGURE 20. Average service operating time and the extended time by EB (10%∼90% L-UE in all UEs).

environment. We can confirm that UE with the EB can stably extend the battery service time, unaffected by the number of L-UE in the cabinet of the train.

Table 2 shows the battery extension rate. This ratio is the UE extended service operating time ratio by EB based on the simulation results Fig. 20. It was confirmed that by using EB, the battery operating time of LTE -60 dBm increased about 1.4 times when the L-UE rate was 10%, and the operating time was extended at about 1.5 times when the L-UE rate was 90%. Similarly, at LTE -115dBm, the operating time was extended about 4.4 times at an L-UE rate of 10% and around 4.6 times at an L-UE rate of 90%. Thus, it can be confirmed that in a train cabin, B-UE can extend its battery service operating time, irrespective of the number of L-UE, from 10–90 %.

VI. CONCLUSION

This paper proposes an energy borrowing transmission scheme, using D2D communication over Wi-Fi direct that borrows and lends energy among cooperating UEs. This process extends the service operating time of UEs with little battery reserve. The performance of EB was examined through measurements and simulations. As shown in Section III and IV, the energy consumption and the data acquisition rates using LTE and D2D links were measured. Their relationship was clarified according to communication quality. Similarly, we analyzed the volume of data received during communications for each quality level of LTE and D2D from various perspectives, such as energy consumption, battery life, and battery depletion time. In addition, Section V outlines the simulations based on these experimental results that verified the increase in service operating time offered by the EB scheme. In our performance evaluation, we confirmed that EB can extend the battery operation time up to 456.8% compared to LTE without EB in a train cabin.

In future work, we will study sophisticated schemes that consider more factors, including L-UE energy consumption models, more efficient methods for finding, choosing, and cooperating with L-UEs, including the control to balance the optimal energy consumption and throughput by considering the D2D link and 5G link in combination. And detailed design and verification for optimizing the economic incentives to encourage energy lending. In addition, this research focuses on the virtual energy lending scheme for a B-UE to access the eNB through an L-UE. Therefore, we did not discuss the energy harvesting (EH) technology in this paper, but we recognize that it is a very interesting technology and prospect. We expect that the EH technology may lead to further performance improvements for our scheme. [46] Specifically, it may be possible to perform EH between UEs during D2D communication.

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