Study on Virtual Energy Borrowing Scheme Using D2D Communication in 5G Cellular System

５Gセルラシステムにおける D2D 通信を用いた仮想電力貸借方式に関する研究

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Abstract

Currently, 5th generation (5G) is being commercially deployed and expanded, and several discussions exist beyond 5G. The main pillars of 5G services are enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (URLLC). These features enable its applications for various purposes and scenarios, such as 4 K videos, smart cities, and self-driving cars. These technologies allow users to enjoy convenient experience. In addition, 5G and beyond 5G is garnering attention and expectations owing to new services and innovative technologies. However, there are still several complaints about smartphones in current cellular network services. One of the significant challenges in next-generation communication is actively resolving the dissatisfaction among existing users. Among them, dissatisfaction with battery life is particularly high, and in the results of “The survey on smartphone satisfaction and dissatisfaction” (Media Marketing Data labo, 2015), over 70% of the users responded that "long-lasting batteries" was the feature they desired in future smartphones. In addition, a survey conducted in 2021 showed that approximately 30% of users felt that their batteries run down quickly after about six months of purchase (Mobile Market, Smartphone Fatigue Survey Questionnaire, 2021).

This result indicates that battery depletion has remained a problem in both the past and present. From the user's perspective, the battery life is important for 5G and beyond. As its use cases expand, we will see improvements in functionality and performance.

As mobile communication becomes more closely connected to our daily lives, the importance of the battery life of smartphones is likely to become crucial. Therefore, this thesis titled “Study on Virtual Energy Borrowing Scheme Using D2D Communication in 5G Cellular Systems” proposes a low-energy consumption communication with Device-to-Device (D2D) communication for 5G and beyond 5G systems.

In this thesis, we attempt to improve user satisfaction for battery performance by using D2D communication to achieve low-power consumption.

Accordingly, Chapter 2 introduces the basics of D2D communication, such as protocols and communication schemes. Previous research has proposed D2D communication based on 3GPP specifications for cellular communication and Wi-Fi for D2D (Wi-Fi Direct, IEEE 802.11). We studied essential D2D communication by extending and combining the 3GPP communication model and the Wi-Fi communication method. In this chapter, we introduce the cooperative communication model and the basic mechanism combining cellular communication and D2D.

Chapter 3 presents an energy borrowing (EB) transmission scheme that is used to conserve the battery life of a UE, such as a mobile phone. EB is based on D2D communication and cellular networks, particularly out-band D2D and 5G networks. This study 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 the UEs with a small battery reserve. EB performance was examined via measurements and simulations. In addition, the energy consumption and data acquisition rates were measured using the LTE and D2D links. Their relationship was clarified according to the communication quality. Similarly, we analyzed the volume of data received during communication for each quality level of LTE and D2D from various perspectives, such as energy consumption, battery life, and battery depletion time. Furthermore, simulations based on these experimental results verified the increase in the service operating time provided by the EB scheme. In our performance evaluation, we verified that EB can extend the battery operation time longer than LTE without EB in a train cabin.

In Chapter 4, we propose an EB transmission scheme that further extends the scheme in the previous chapter, to consider the power burden and fairness of UEs that lend their own battery resources. The proposed system in Chapter 3 does not consider the fairness and burden of the lenders, and it is essential to focus on lenders, to improve the efficiency of the system. We propose a scheme with high fairness that reduces the burden on the UEs that lend their own battery resources compared to the existing scheme. This scheme selects the best UE from the neighboring UEs to avoid a heavy burden on the UEs that lease power. When the borrowing UE has multiple candidates for the lending UEs, the borrowing UE selects the most suitable UE by considering the remaining battery power of the other UE and parameters, such as the communication status of D2D and 5G. In this study, we measured the power consumption of the UE on the lending and borrowing sides, then simulated and evaluated the performance using the actual measurement results.

In Chapter 5, we conclude the paper and suggest possible future research directions. In this study, we proposed the concept of borrowing battery resources via communication and designed a scheme accordingly. In the future, various developments are expected, including a scheme that considers user behavior and an analysis of overall cellular system performance. In this chapter, we introduce these expectations for the future of this research.

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Chapter 1

Introduction

Recently, 5th generation (5G) cellular system services underlined by 3GPP standardizations are being launched successively, and the future of mobile communications is expected to expand beyond the 4th generation (4G) era. The main pillars of 5G services are enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC), including ultra-reliable and low-latency communication (URLLC). These features enable its application for various purposes and scenarios, such as 4 K videos, smart cities, and self-driving cars [1]. Simultaneously, the volume of global mobile data traffic is expected to continue to increase, reaching 607 EB/month in 2025 and 5016 EB/month in 2030 [2]. Furthermore, additional targets have been set for beyond 5G (B5G). Specifically, Japan's Ministry of Internal Affairs and Communications' Beyond 5G strategy targeted a 10 times higher eMBB data rate, 1/10th of the delay latency compared with 5G, including other improvements [3].

A major challenge in next-generation communication is to actively resolve the points of dissatisfaction among existing users. Several complaints about smartphones remain. Among them, the dissatisfaction with battery life is particularly high, and in the results of the survey [4], over 70% of the users responded that "long-lasting batteries" was the feature they desired in future smartphones. Battery life is one of the most common user complaints. In that survey, 61.6% confirmed a high degree of concern when responding to the questionnaire of "fear of the smartphone battery running out when going out, i.e., leaving their homes," as demonstrated by [4].

In addition, a survey conducted in 2021 demonstrated that 30% of users who had purchased the product for approximately six months, and approximately 49% of users who had purchased the product for approximately two years felt that their batteries were running low quickly [5]. These results indicate that battery life is easily perceived as unsatisfactory by users and is considered an important factor when using a smartphone.

From the user's perspective, improved battery life is expected for 5G and B5G. In addition, use cases will expand, and enhanced functionality and performance will be observed. Issues closely related to user dissatisfaction with battery life, as described here, can be critical in present and future mobile communications. To contribute to the solution of these problems, this study proposes the concept of the energy borrowing transmission scheme based on device-to-device (D2D) communication.

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

The objective of this research is to solve the problem of battery life of user equipment (UE), in which users are likely to be dissatisfied, and to contribute to an increase in satisfaction when using a smartphone. In addition, D2D communication technology has been actively studied to expand coverage areas and address disaster situations. This research applies D2D technology to reduce the battery problem and proposes a power borrowing and lending method as an approach to address the battery life issue, which has been a problem for some time.

The main contribution of this paper is to design and propose an energy-borrowing transmission scheme based on D2D communication. The research on D2D communication has often focused on issues such as coverage. The concept of using communications to virtually borrow power has not been previously considered, and there is no precedent for previous research on such a system. Therefore, this study defines and proposes a novel concept of using D2D to virtually borrow power from other terminals over communication, and designs a system based on this definition. Based on this scheme, we approach the problem of battery life, which is one of the most common complaints of several users.

1.1 Research Background

D2D communication has been extensively discussed and researched. Various improvements in the performance index parameters have been discussed in previous studies, such as coverage enhancement in [6], throughput improvement in [7-8], spectrum efficiency in [9-10], and energy efficiency in [11][12]. Similarly, the 3GPP released 12 has standardized the technical specifications of the Proximity Service (ProSe), which discovers nearby user devices on an LTE network and direct communication between devices [13], [14].

Moreover, D2D is expected to function as a means of communication when a base station or conventional network becomes unusable during disasters, owing to the inability of the devices to function without the use of a base station or core network. Research on communication using D2D as a form of information infrastructure during disasters is garnering increasing attention [15-17].

As stated above, D2D communication has various applications and is expected to affect energy efficiency. In [18] and [19], the D2D protocol was designed for a scenario involving a cluster using Wi-Fi Direct. Reference [20] implements and demonstrated multi-hop communication using Wi-Fi. Reference [21] compares the energy efficiency when using Wi-Fi and LTE for video streaming. In addition, this study validates the energy efficiency and throughput of D2D. Similarly, various studies have been conducted on active communication methods for out-band D2D using Wi-Fi [22-24]. In addition, various studies have been conducted to increase energy efficient via access control, channel allocation control, and relay selection methods [24-27].

Hence, various aspects of D2D communications are being considered to improve coverage, throughput, frequency efficiency, and energy efficiency. D2D communication is also expected to be used by 3GPP because standardization technology for the ProSe function has been defined by 3GPP Release 12. However, because there is no research that focuses on battery life using D2D technology, we decided to study a communication method for the purpose of battery life, which is a common complaint of users.

Therefore, because D2D communication is attracting attention and is expected to have high power efficiency, this research approach is based on the idea that battery life can be extended by making good use of D2D communication technology.

1.2 Challenges and Motivations

As mentioned earlier in the introduction of previous studies, the objectives of the D2D research field have conventionally been to increase communication distance, coverage area, and data rate. In addition, much research has been conducted on the power efficiency in the D2D field. However, the main purpose of these studies was to improve the overall system-wide power efficiency or even the power efficiency of individual devices. Therefore, these studies do not focus on improving the user experience from the user's perspective. However, this paper proposes a method to extend battery life by virtually borrowing power from nearby users, although communication with the base station is possible only when the battery is insufficient from the user's perspective.

In the D2D communications field, D2D focuses on improving coverage, throughput, frequency efficiency, and energy efficiency. However, there have been studies on power efficiency in this area, yet no research has focused on borrowing power from other terminals. In addition, various novel efforts are underway to address this issue at the market level. For example, Samsung's Galaxy S10, released in 2019, added a feature called wireless power sharing [28]. This feature is a power supply function that uses wireless power transmission technology to physically supply power to other devices by placing the other device (or peripheral) on the smartphone.

Although various efforts have been made at the product level to incorporate high-capacity batteries, adopt power-saving modes, and wirelessly share power among mobile terminals via contactless power transfer, there remains no prior research on the concept of using communication to virtually borrow battery resources from other terminals. Therefore, one of the motivations of this research is to provide a novel communication method based on this concept. Therefore, this thesis proposes a communication scheme based on D2D communication using Wi-Fi Direct (IEEE 802.11).

The second motivation is the fairness of the scheme. After studying the basic communication scheme, it was necessary to improve the system of this method from the perspective of fairness. Borrowing power from another terminal implies that the lender's battery is lent to the other terminal, and thus the battery runs down faster. Therefore, we examined a model that considers the fairness of this system and the power burden on the terminal on the side of the battery resource lender. The advantage of this extension is that the system model accounts for the burden on the lending terminal's battery resources; hence, the lender can control the decrease in the battery power. By ensuring fairness, it is possible to prevent phenomena such as the battery running down faster, only for certain terminals. Accordingly, it contributes to ensuring fairness in the system.

The challenges and motivation of this paper are summarized as follows;

- To address the recent major issue of battery life for individual users, this study proposes a novel concept and method of virtual leasing of battery resources through D2D communication.
- Conventionally, prior studies on D2D communication have focused on power efficiency. The authors have also considered the power consumption of the entire system. This has also been discussed in terms of how to save power in D2D communications. However, no concept focuses on individual user satisfaction and uses D2D communication to lease the battery resources of other devices to virtual adversaries.
- This study focuses on individual user satisfaction, creates a concept of borrowing battery resources from other terminals using D2D communication, and proposes a communication scheme.
- In addition, this research is based on the novel idea of using D2D communication to prolong battery life, rather than power saving in D2D communication.
- This research has the potential to resolve user dissatisfaction with the battery running time of a smartphone.
- The effectiveness of the proposed method was verified. Specifically, we conducted experiments and analyses to clarify the power consumption of LTE and D2D. In the simulation, the experimental results are adopted to evaluate the results based on a

specific use case of how many minutes a user can use a smartphone in a real environment.

- As described above, the approach that focuses on individual user satisfaction via the virtual lending of battery resources by D2D is unique and novel.

1.3 Contributions

The main contributions of this thesis can be described in the following two points: one is a study on the proposed energy-borrowing transmission scheme based on D2D communication, and the other is a study on a more extended version of the proposed scheme.

In Chapter 3, we conduct a basic study of the energy-borrowing transmission scheme based on D2D communication. This paper presents a basic study of the scheme and introduces a method that enables the extension of battery life by applying D2D communication to cellular systems.

The main contributions of this chapter can be summarized as follows.

- A basic concept is proposed to borrow battery resources virtually from other terminals using D2D communication techniques.
- Incorporate D2D communication using Wi-Fi Direct into cellular systems, and design a basic protocol for power borrowing and lending schemes.
- The difference in power consumption by the reception strength level between LTE and D2D is clarified via experiments using actual equipment.
- The experimental results verify that D2D communication technique consumes less power than LTE.
- Because the experiments were conducted not only in the laboratory, further experiments were conducted in multiple outdoor areas to confirm that D2D has lower power consumption than LTE in multiple typical environments. Hence, it is verified that the proposed scheme is effective in multiple environments and scenarios, and not just in a single scenario.
- Simulation analysis using experimental results confirmed that the proposed method is capable of extending battery life.

In Chapter 4, we study the power burden on the lending terminal and fairness of the proposed scheme by setting an upper limit for power lending to the scheme proposed in Chapter 3. In this study, we set an upper limit on how much power a terminal on the lending side is allowed to lend per day, including an upper limit on how much power it is allowed to lend in a single session. We considered a method that incorporates an upper limit. This would avoid a situation in which only certain terminals that lend power and the battery are discharged. In addition, the upper limit makes it possible for multiple terminals to lend power in small amounts, thereby ensuring the fairness of the scheme. In addition, in previous schemes, both the parties borrowing and lending power had to be determined by multiple factors, such as the remaining battery capacity and the quality of communication with the base station, before initiating communication. However, redundancy was eliminated, and a more efficient scheme was designed.

The main contributions on this chapter of the thesis can be summarized as follows.

- The method is extended by considering the power burden on the terminal to which battery resources are lent by setting an upper limit on the amount of lending power.
- The burden on the lending terminal's battery resources was controlled by introducing two limits to the system: the maximum amount of power to be lent per day and the maximum amount of power to be lent per session.
- The aforementioned upper limit makes it possible for multiple terminals to lend a small amount of power, thereby extending the method to ensure fairness.
- Here, we eliminated the redundancy of the method proposed in Chapter 3 and improved the efficiency of determining the borrower, which is a terminal with a low battery.
- Experiments using actual equipment demonstrated the power consumption of both the borrower and the lender. The burden on the borrower is also clarified by comparing the borrowing side to normal communication.
- The simulation evaluation using the experimental results confirmed that the upper limit is a method that considers fairness.

- Similarly, we analyzed the burden on the lender and battery running time of the borrower by setting an upper limit through simulation evaluation.

1.4 Thesis Structure

The remainder of this thesis is organized as follows. Chapter 2 describes D2D communication as the foundation of the proposed method and provides a comprehensive context for the proposed method. In Chapter 3, the proposed method using D2D communication “Energy borrowing transmission scheme” is explained. Experimental and simulation results are discussed to verify the effectiveness of the proposed method. In Chapter 4, we propose an extension of previous work by setting an upper limit on the amount of energy that can be lent out, thereby considering fairness. The experimental and simulation results demonstrated the effectiveness of the proposed scheme. In Chapter 5, we conclude the paper and suggest possible future research directions.

Chapter 2
Fundamentals of D2D Communication

2.1 Introduction

D2D communications have been studied for years. The objective of this study is to extend the battery operating time of mobile terminals using D2D communication. Therefore, in this chapter, we introduce the basic technologies of D2D communication. First, an overview of mobile ad hoc networks (MANET) and their mechanisms, which are the basis of D2D communication, is introduced. Subsequently, typical protocols for MANET are explained. This knowledge was provided by [29][30].

Next, the protocols of previous studies, which form the basis for the communication protocol design of this study [18][19], are introduced. This study proposed a protocol for combining Wi-Fi direct and LTE communications.

2.2 MANET Routing Protocol

Research on D2D communication has been ongoing for years. D2D communication is a communication method in which terminals communicate directly with each other, and the MANET working group (WG) of the Internet Engineering Task Force (IETF) has been working on the development of a multi-terminal D2D communication system; in addition, the standardization of hop radio communication has been under discussion since 1997.

In a MANET, the communication is solely achieved by nodes (devices). It does not require wireless LAN access points or mobile network base stations. Therefore, communication is not affected by location or environment, and communication is achieved by building a network among the nodes gathered at that location. Nodes search for communication partners and communicate directly with one another.

The features of MANET are summarized as follows:

- Nodes are user's terminals (devices).
- Nodes are movable.
- Nodes configure a temporary, ad hoc network and communicate with each other.
- The network is solely comprises nodes, without requiring wired or mobile base stations or access points.
- The network topology may change frequently owing to node movement.

Next, communication methods and MANET types are presented. Figure 2-1 illustrates single-hop communication. Because the source and destination nodes are in close proximity and radio waves can reach them, direct communication is achieved, thereby allowing these terminals to communicate directly. This communication scheme is known as single-hop communication. However, in Figure 2-2, the source and destination nodes are far apart, and radio waves cannot reach them; hence, direct communication is impossible. Therefore, packets are passed to neighboring nodes and relayed by relay nodes. This communication method is known as multi-hop communication. By adopting multi-hop communication, devices can communicate with distant terminals that cannot be directly reached by radio waves. In Figure 2-2, only one relay node exists; however, there may be multiple terminals. The mechanism for forwarding packets and communicating in this manner is called routing, and routing protocols are being actively studied in the ad hoc networking field.

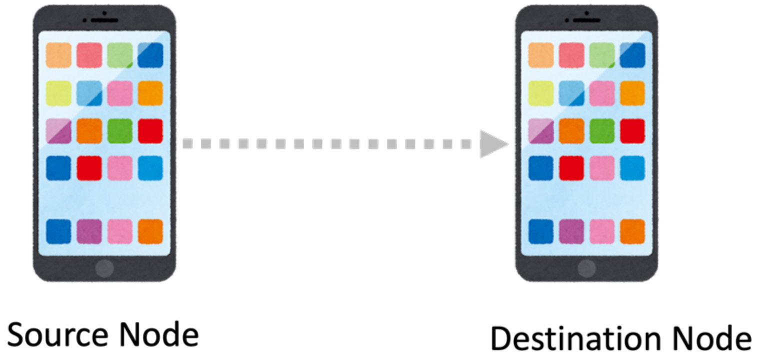

Figure 2-1 Single-hop communication

Figure 2-2 Multi-hop communication

MANET are expected to play an active role in various applications, including disasters, sensor networks in factories, agriculture, and warehouses. Some of these applications are listed below.

(1) Applications during disasters.

- Search, rescue, emergency reporting, and evacuation guidance by police and fire departments in the event of a large-scale earthquake, fire, tsunami, or typhoon
- In addition, collection of disaster information, support for recovery efforts, safety confirmation, and information exchange among disaster victims

(2) Mobile Networks and Wireless LAN-based multi-hop services

- Information transmission and management in factories, product warehouses, construction sites, agriculture, etc.
- Advertisement distribution and navigation in shopping centers, theme parks, event venues, and stadiums
- Crime prevention, disaster prevention, and environmental monitoring using sensor networks

Figure 2-3 presents the classification of routing protocols for MANETs. Topology-based routing protocols can be broadly divided into three types: proactive, reactive, and hybrid protocols. Location-based types also exist.

In the proactive type, each node periodically exchanges information about routes with other nodes in the background to create and maintain a routing table, even when no communication request is generated. A typical example is the OLSR.

In the reactive type, the communication route is constructed after a communication request is generated. The reactive type builds a communication path after a communication request is generated and maintains that information for a certain period. Although there is a delay between the occurrence of a communication request and the start of communication, when there are few communication requests, the control overhead is small, and power consumption can be minimized. A typical example of the reactive type is DSR.

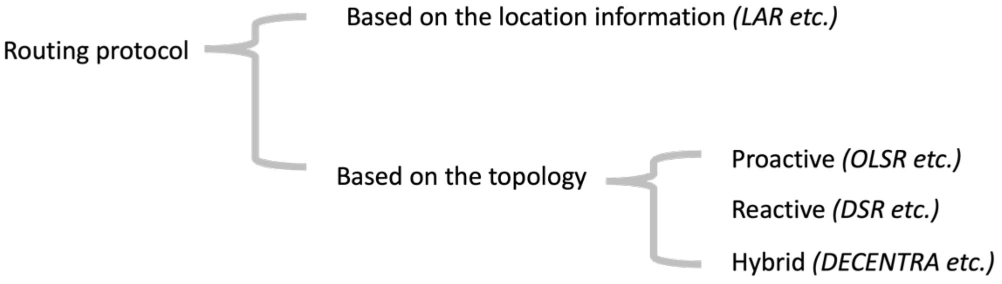

Figure 2-3 Classification pf MANET routing protocol

2.2.1 DSR Protocol

The dynamic source routing (DSR) protocol, a reactive-type protocol, is one of the protocols proposed by the IETF MANET WG. Therefore, a route search was performed after a communication request was generated. The node sending the packet specifies the overall route, and the relay node sends the packet to the endpoint according to that route. Because a route is created after a communication request occurs, there is a delay; however, this limitation is compensated for by storing the route as a route cache. In DSR, a terminal with a communication request broadcasts a route-request packet to the surrounding terminals. When the surrounding terminals receive a packet, they first check it. If it does not know the destination, it adds its own terminal information to the routing information in the packet and sends it to surrounding terminals. However, if the routing information in the route request packet contains the terminal's own terminal information, the packet is discarded to improve the efficiency.

2.2.2 OSLR Protocol

The Optimized Link State Routing (OLSR) protocol is a proactive routing protocol. Instead of constructing a route after a communication request, a route table is created in advance. Each node periodically communicates with the other nodes and exchanges routing information to create a routing table.

Information propagation in which a node broadcasts its own routing information to other nodes is called flooding. The proactive routing protocol has the advantage of short latency, although it has an overhead owing to periodic communication.

When every node sends information to all its neighbors, the amount of traffic increases. Therefore, the OSLR protocol is characterized by the use of a multipoint relay (MRPs) protocol for more efficient flooding. The nodes maintain information up to two hops ahead through the periodic exchange of routing information. The MRP set is then determined based on this information. This set is the minimum number of neighbors that can forward packets to the node two hops ahead; only the nodes in this set can send information, thereby avoiding the duplication of information transmission and reducing the amount of traffic.

2.3 D2D Protocol in Cellular Networks

This section presents the basic concepts and representative protocols of D2D communication; however, these are theoretical models. From this perspective, we introduce previous studies based on real systems.

[18][19] proposed a D2D communication scheme that combined cellular communication and Wi-Fi. The scheme proposed in this study enables D2D communication using Wi-Fi in cellular communication by extending the protocols of existing systems. The proposed method is designed based on the protocols and architecture of existing systems and is an excellent study that focuses on practicality. Wi-Fi is currently used in many devices and is expected to be used in actual applications. Figure 2-4 shows the schematic of the system concept.

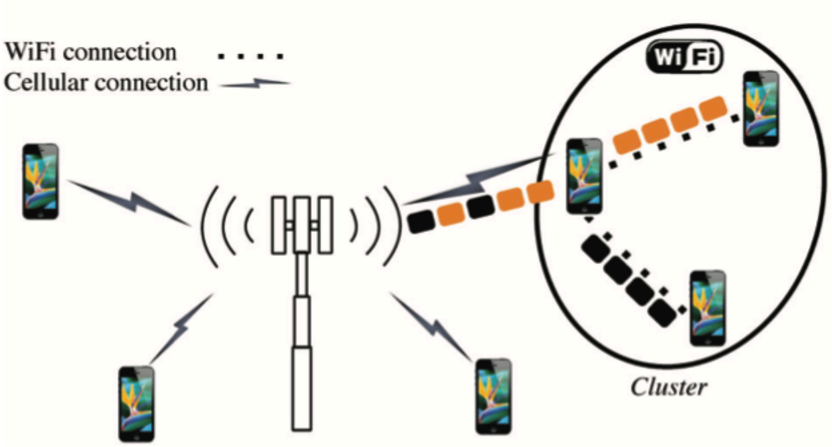

Figure 2-4 A D2D architecture for boosting LTE cell performance using infrastructure-less Wi-Fi between mobile devices [18]

The right-hand side of the figure shows the scheme proposed in a previous study. As shown in the illustration, UEs form clusters using Wi-Fi. A UE was selected as a representative of the cluster (group owner: GO) and communicated with the base station. The GO aggregates the communication data of the UEs in the cluster using Wi-Fi, and communicates with the base station using cellular communication.

Clusters are formed by users who wish to use D2D communication. They are formed by two types of cluster heads, GOs and clients. The cluster heads were selected from terminals with the best cellular communication quality. The cluster head is not fixed but varies depending on the situation. Additionally, D2D communication by the clusters is performed when the data rate is higher than the cellular rate because of the use of Wi-Fi by the cluster members.

The following is an introduction to the flow of cluster formation in previous studies.

1. Search and Discovery. A UE wishing to join a group scans the IEEE 802.11 channel for existing groups.
2. Group Ownership Negotiations. The UE is notified of information such as the intent value, which is a number between 0 and 15, indicating the UE's willingness to become a GO, and the UE with the highest intent becomes the GO. In the proposed scheme [18], the UE selects the intent value based on the LTE channel quality indicator (CQI).
3. Security Setup and IP Address Assignment. The GO initiates a Wi-Fi security setup using a wireless protected setup (WPS). When the security setup is complete, an IP address is assigned to the client, according to the DHCP protocol.
4. Standard Wi-Fi direct procedures were used for the communication. However, the method in [18] allows the GOs to be changed. Direct Wi-Fi specifications

do not allow the transfer of group ownership. However, in [21], the GOs can be changed.

5. A GO change occurs when the eNB detects that another cluster member has a better cellular channel quality (CQI) than the current GO.

A unique feature of this scheme is that the cluster client sends an LTE ID notification message containing its own LTE ID to the cluster head (GO). The GO then broadcasts a Wi-Fi-LTE ID association table containing the LTE and Wi-Fi Direct IDs of all cluster members. This helps the GO to switch smoothly.

Security is also important in D2D communications. In this prior study, security was ensured as follows:

When a cluster is created, the evolved Node B (eNB) sends a security mode command to the cluster head for each cluster member. The cluster head sends this message to members using Wi-Fi. When a member receives the message, it sends a response to the cluster head. The cluster head then forwards the message to the eNB. This provides security verification. The cellular network verifies that the cluster member is correct by performing security verification using the CH.

Prior research also recommends including each member's intent value (average CQI) in the security-mode command. The eNB knows the actual CQI, so each member can verify the correctness of the values reported by the other members. If an unusual value is detected, the member is ejected.

Chapter 3

Energy Borrowing Transmission Scheme employing D2D Communication

3.1 Introduction

In this chapter, we propose an energy borrowing (EB) transmission scheme that is used to conserve the battery life of user equipment (UE), such as mobile phones. EB is based on device-to-device (D2D) communication and cellular networks, particularly out-band D2D (Wi-Fi Direct, IEEE 802.11) and 5G networks. Because 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 packets of the low remaining battery UE to/from the gNB (5G-base station). Because the nearby UE plays an active role in the connection of the low-remaining battery UE with the gNB, the low-remaining battery UE virtually borrows the battery resource of the nearby UE. This chapter introduces the operation protocol and procedure followed by EB using Wi-Fi Direct and 5G networks. Experiments and simulations demonstrate that EB can extend the terminal battery running time, and is more effective than the existing scheme that uses only the cellular network.

3.1.1Related Works

In this section, we present research related to this study. As mentioned earlier, D2D communication has been studied for its various advantages such as coverage enhancement [31] and throughput improvement [32]. It is also expected to be useful in various scenarios, such as disasters, agriculture, and improvement. [29] In this context, this study focuses on improving the power efficiency of D2D communication.

Previous study [21] has mentioned the power efficiency of D2D communication, indicating that it is more power efficient and consumes less power than cellular communication. Inspired by this, they hypothesized that it may be possible to extend the battery life of mobile terminals by effectively using D2D communication, taking advantage of the fact that it has lower power than cellular communication.

We also inferred that D2D communication could be used to extend battery life when users are in trouble because of the low battery power in environments where there are no recharging facilities, such as when they are out and about. This was the approach used in this study.

This study was based on the protocol of a previous study [18][19] as a reference. In this study, D2D communication was performed using WiFi Direct. This is because the protocol design is based on an actual communication standard and thus has high expectations for practical use. Another reason is that many terminals currently support the Wi-Fi standards.

In these studies, Wi-Fi was used to create the D2D clusters. The cluster head communicates with the base station. The cluster head was chosen to establish the best cellular quality. Additionally, there were clients in the cluster.

In contrast, because the objective of this research is to maximize the battery life, several conceptual differences occur: D2D communication is performed only as necessary, and both D2D and cellular communication are not performed when there is no communication request. This reduces the battery power. Moreover, clusters were not created and one-to-one communication was performed. The energy borrower terminal selects the terminal with the lowest power consumption for D2D communication. Thus, the terminal selection criteria for D2D communication are different.

3.1.2 Contribution

This study proposes a communication scheme based on a novel concept that adopts D2D communication to borrow battery resources from surrounding terminals only when the battery is low. The communication scheme will be designed based on cellular communication and Wi-Fi Direct, which is a widely used communication standard for smartphones, and thus has high feasibility.

Although existing studies have focused on improving the power efficiency of D2D communication, the idea of adopting D2D communication to extend battery life is novel in this research. Another novel idea is considering power consumption and battery run time based on individual users rather than the power consumption of the entire system.

In addition, the evaluation was performed via experiments and simulations. Experiments were conducted using actual smartphones to measure the power consumption. The simulation is devised to verify the results using the results obtained from the experiments, such that it is close to the actual environment.

The contributions of this research are summarized as follows:

- We proposed a novel communication method that focuses on users' individual satisfaction and virtually borrows battery resources from the surrounding terminals using D2D communication.
- Via experiments with actual smartphones, we clarified the power consumption when using D2D communication to virtually borrow battery resources from other terminals and the power consumption when using cellular communication.
- The experiment was conducted in an anechoic chamber to reproduce multiple communication environments for both D2D and cellular communications. This allows us to clarify the power consumption for each reception strength in detail. In addition, we tested the proposed method in multiple real-world environments to determine its effectiveness in a typical environment.
- The simulation using the results of the experiment elucidated the effect of the proposed method on extending the battery life.

3.2 System Model

3.2.1 System Model of the Energy Borrowing Transmission Scheme in Cellular System

First, this section presents an overview of EB and its usage scenario. Fig. 3-1 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 [18] and [19], 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.

3.2.2 Flow of the Energy Borrowing Transmission Scheme in the Cellular System

The flow of the proposed scheme is explained below, regarding Fig. 3-1 and Fig. 3-2. shows the sequence diagram for the scheme. In our scheme, L-UE executes EB when its remaining battery, and its 5G connection are sufficient.

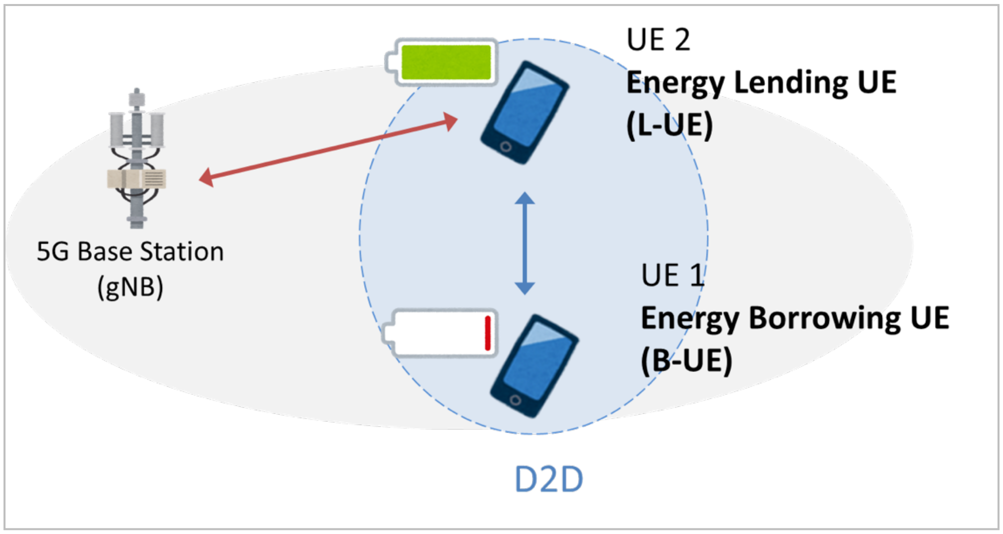

Figure 3-1 Overview of the energy borrowing transmission scheme

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.

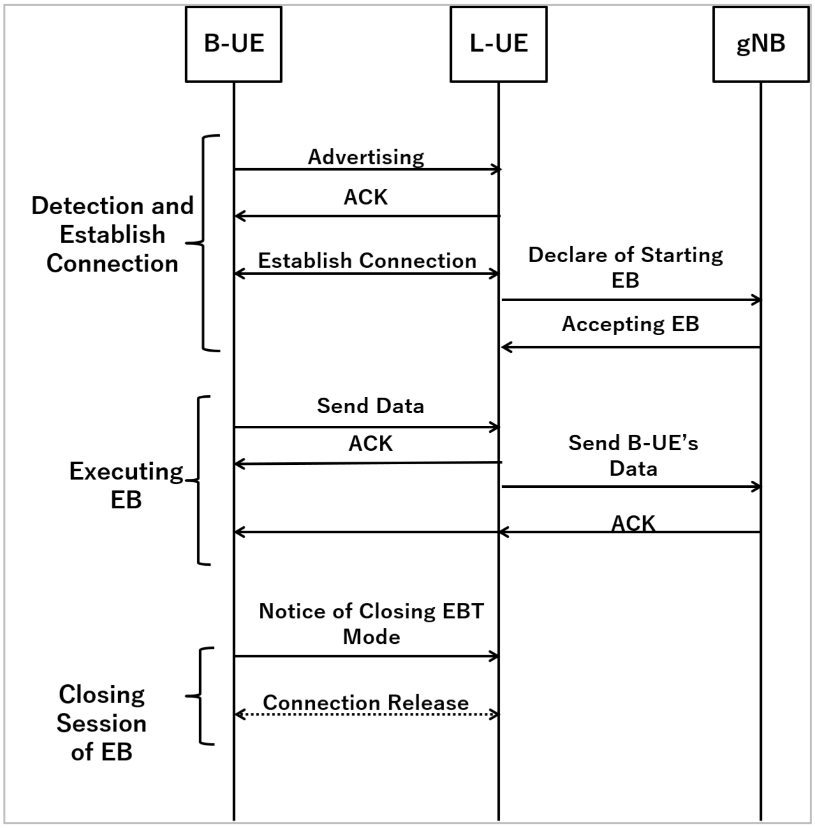

Figure 3-2. Sequence diagram of EB

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.

3.2.3 Protocol and Procedure of The Energy Borrowing Transmission Scheme

Fig. 3-3 shows the procedures as the sequence diagram. In this study, the communication protocol is designed with reference to prior works [18][19]; it is based on the LTE system, but the basic concepts and flow remain the same for 5G. Therefore, it is also expected to be applicable to 5G systems.

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. 3-3, L-UE candidates are UE 2 and 3.

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 3.3.

In Fig. 3-3, 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 [18][19]. 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 [18],[19],[39], and [40], we use the same technique as in [18][19] 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.

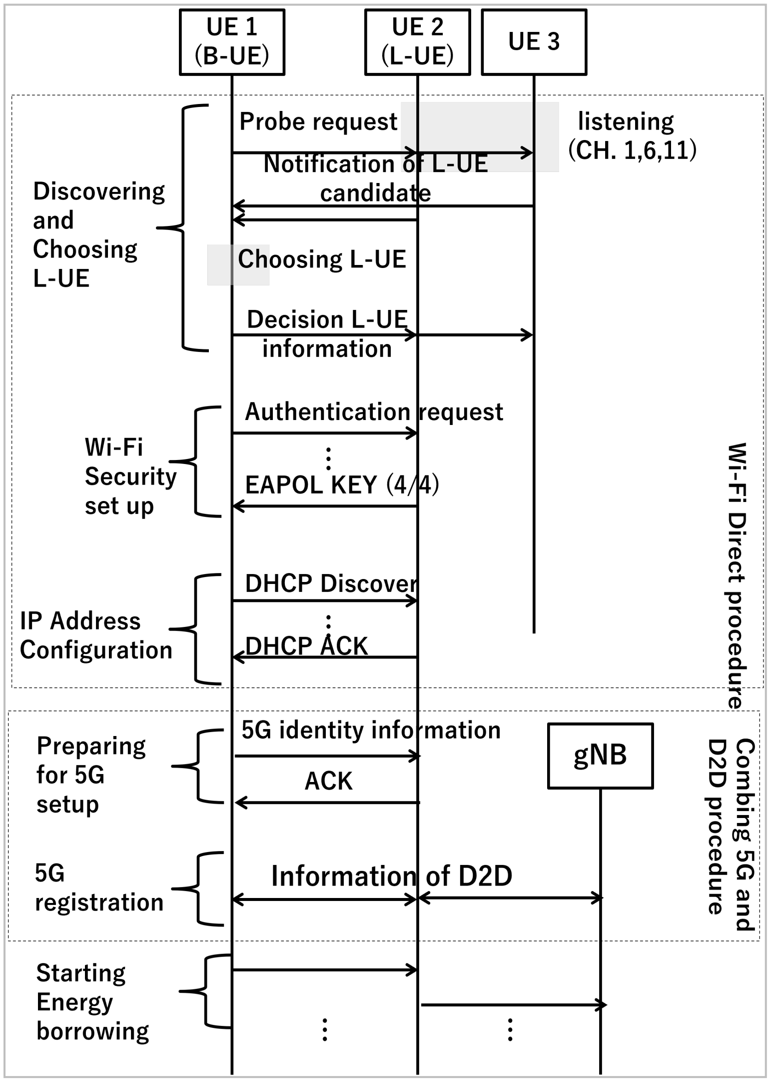

Figure 3-3 Procedure for Wi-Fi Direct and 5G in EB

3.2.4 Flow of B-UE and L-UE in EB

Herein described is how B-UE and L-UE respectively operate in EB. Fig. 3-4 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 > Thssi (θrssi), and L-UE's CQI (Channel Quality Indicator) with 5G (θcqi) > Thcqi, and the battery remaining of L-UE > Thrembat (θrembat), 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. 3-5 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} (θ_{rssi}), and other conditions; CQI of 5G, and battery remaining. If all conditions are satisfied that means CQI > Th_{cqi} (θ_{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.

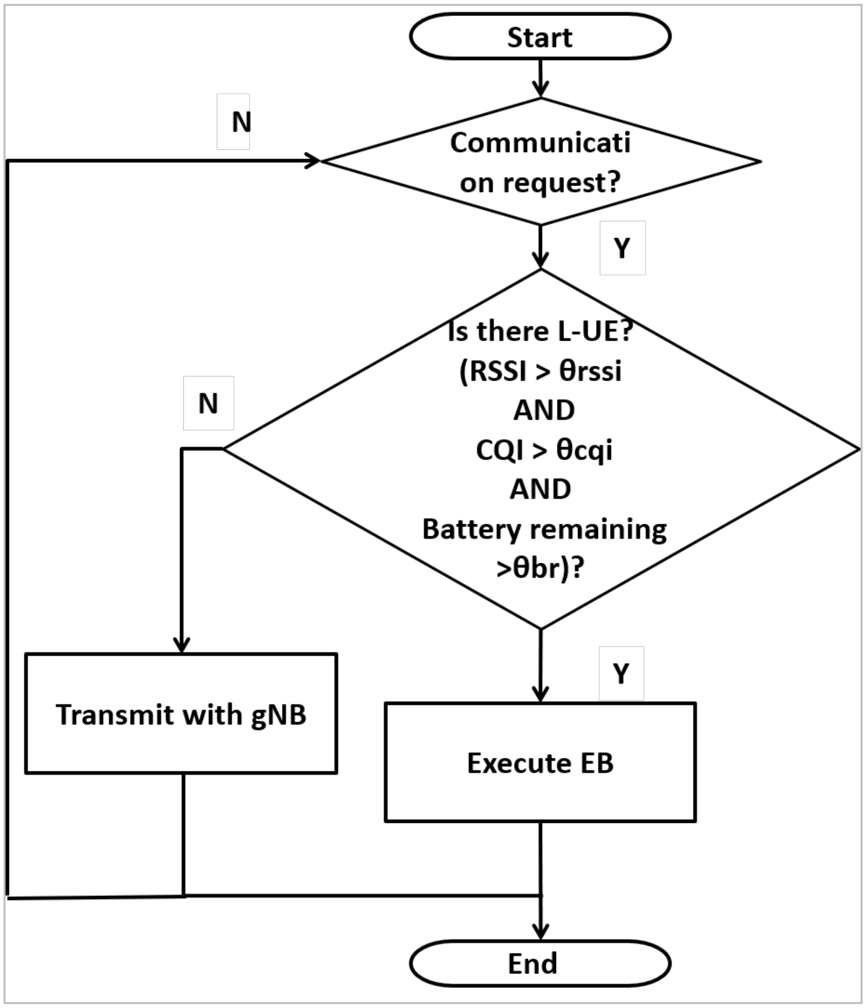

Figure 3-4 Flowchart of B-UE operation in EB.

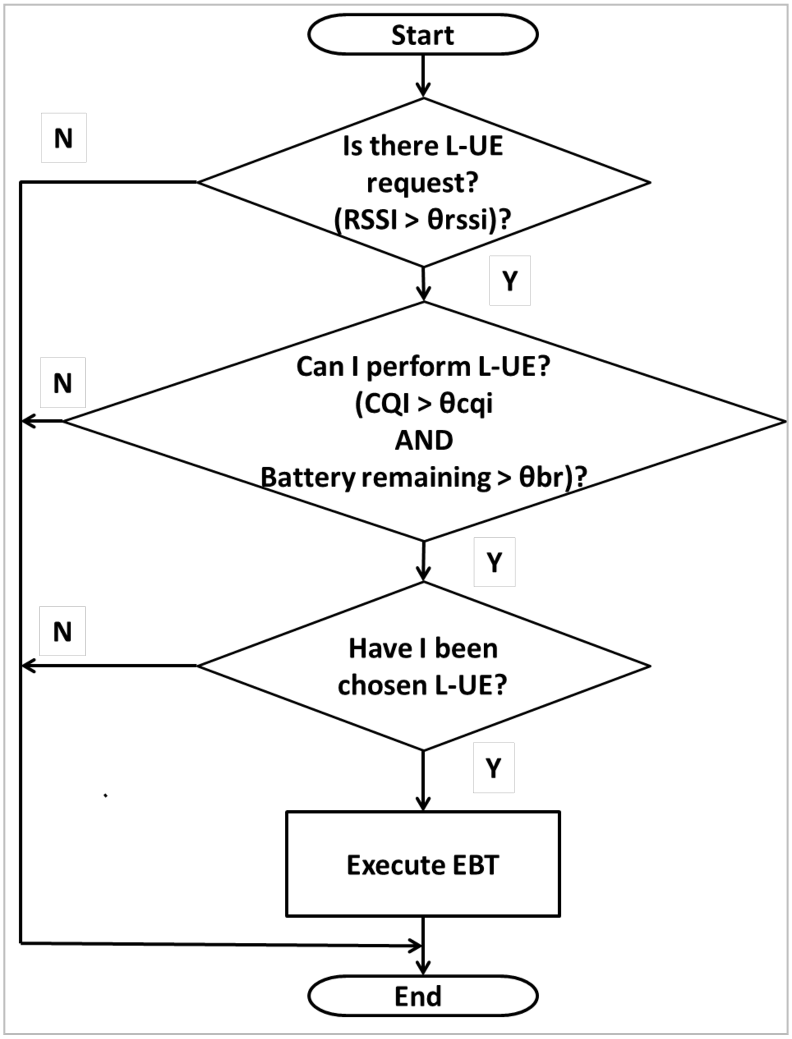

Figure 3-5 Flowchart of L-UE operation in EB.

3.3 Basic Measurement Experiment

This research has two phases: experiments and simulations. First, we measured and analyzed the power consumption and download speed of D2D and LTE using a smartphone. And the second, 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.

3.3.1 Measurement Set Up

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. The experiment was conducted using LTE-enabled smartphones. This was because the LTE environment was the only option available at the time of the experiment. However, in terms of the comparison between cellular and D2D communication, the outcome of the comparison is the same, and it can be deduced that there are no problems in the evaluation of the method.

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 between the base unit and base station during 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. The file was uploaded to the online storage while tracking the energy consumption and all the processes of the smartphone.

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. 3-6 shows the energy consumption and download speed in D2D -65dBm. The X-axis represents time. And the Y-axis represents the energy consumption (current) and the download speed. Notably, the energy consumption (red line) increased since the download started at the 30 s mark. We can observe the download speed (blue line) in the graph. We calculated the amount of data that could be acquired per unit of power using these measurement results.

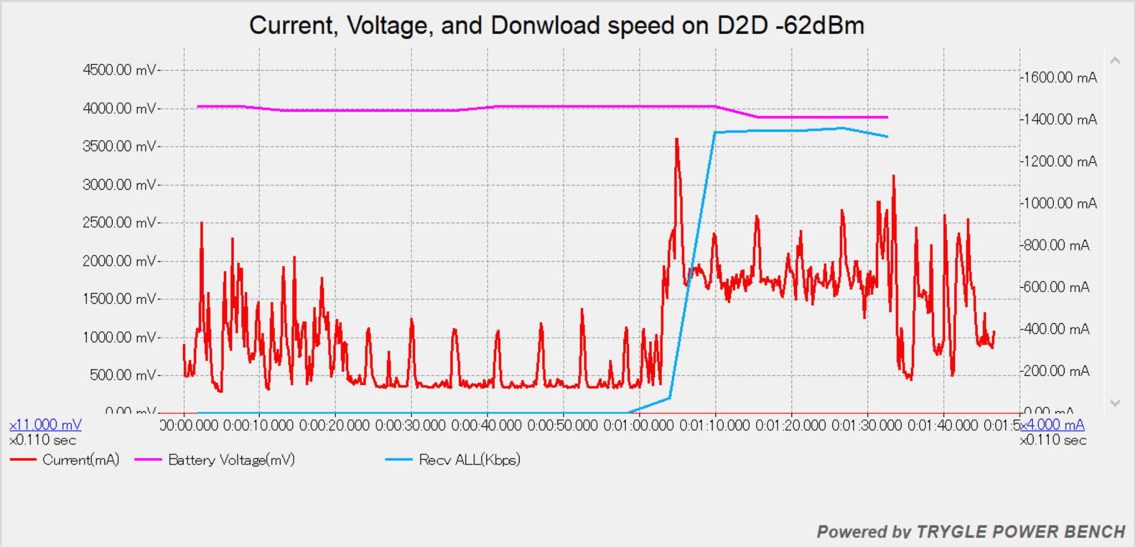

Figure 3-6 Energy consumption and download speed in D2D -62dBm

3.3.2 Measurement Results

In this section, the experimental results are presented. First, Fig. 3-7 shows the average energy consumption during data downloading. The Y-axis is the energy consumption J/Second, 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.

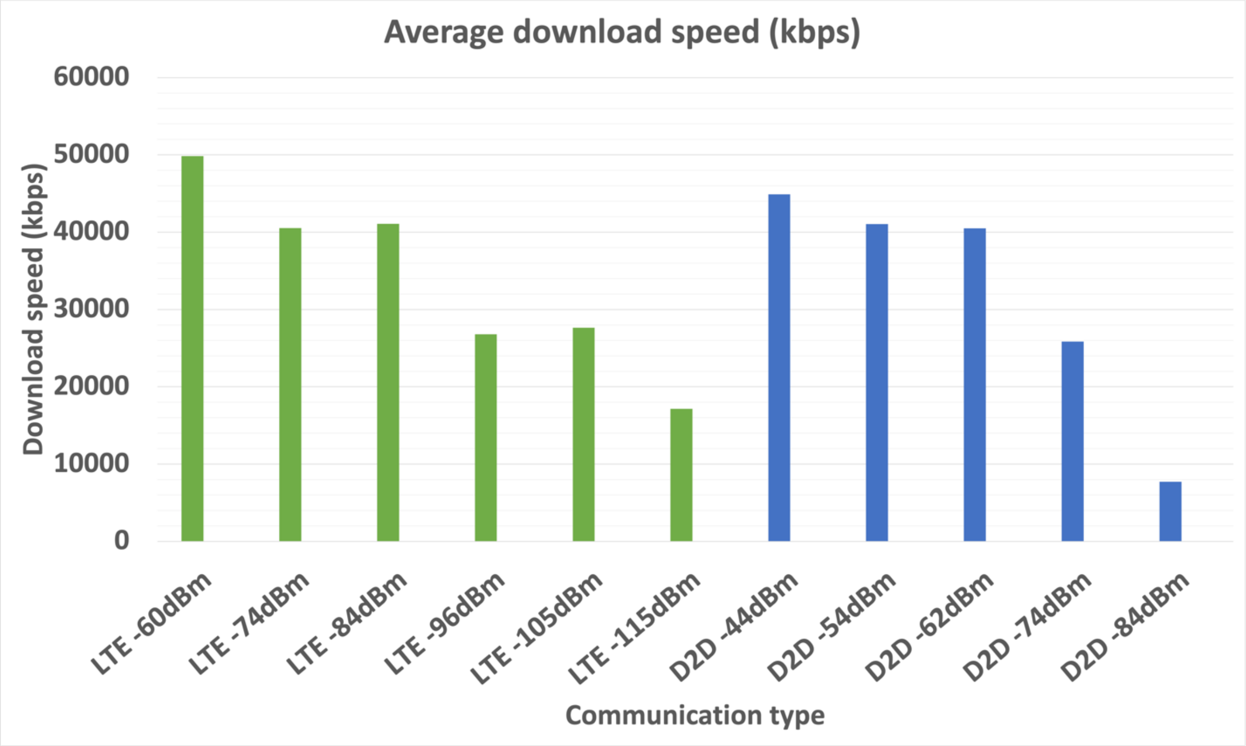

Figure 3-7. Average energy consumption in data downloading on LTE and D2D

Fig. 3-8 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.

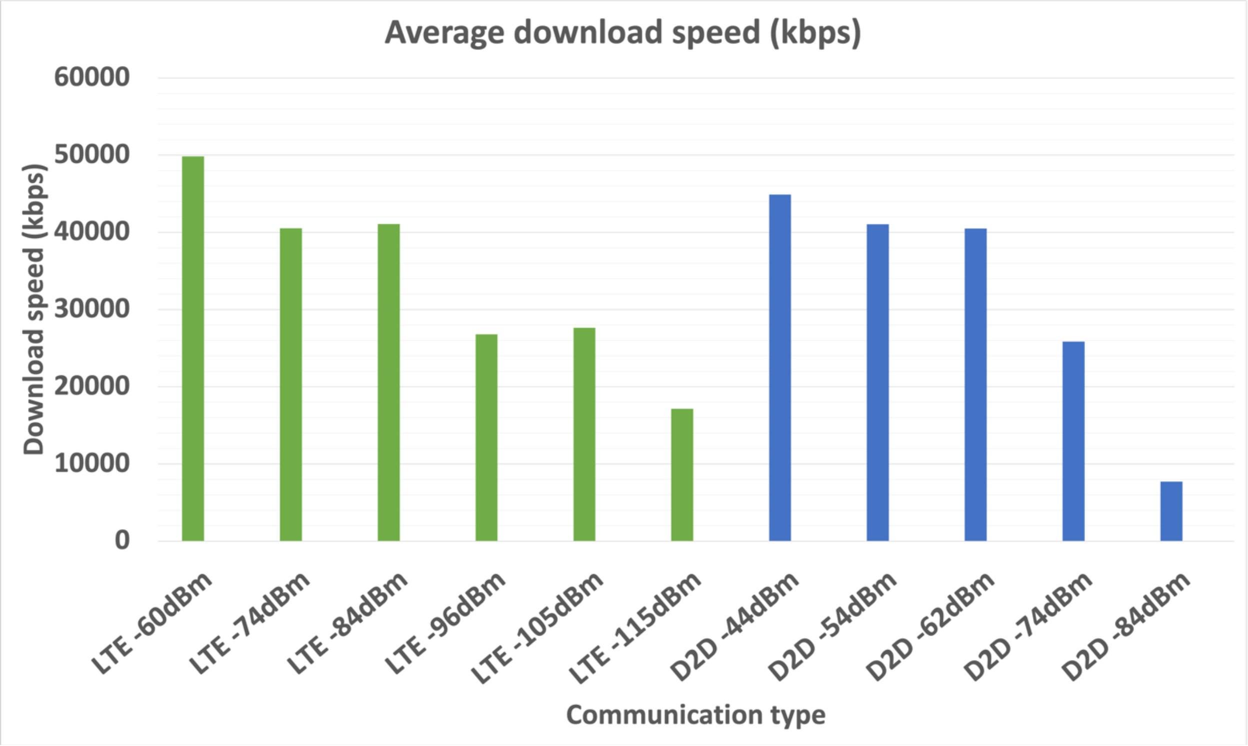

Figure 3-8 Average download speed on LTE and D2D

Fig. 3-9 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. 3-10 shows the energy when downloading 100 MByte (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.

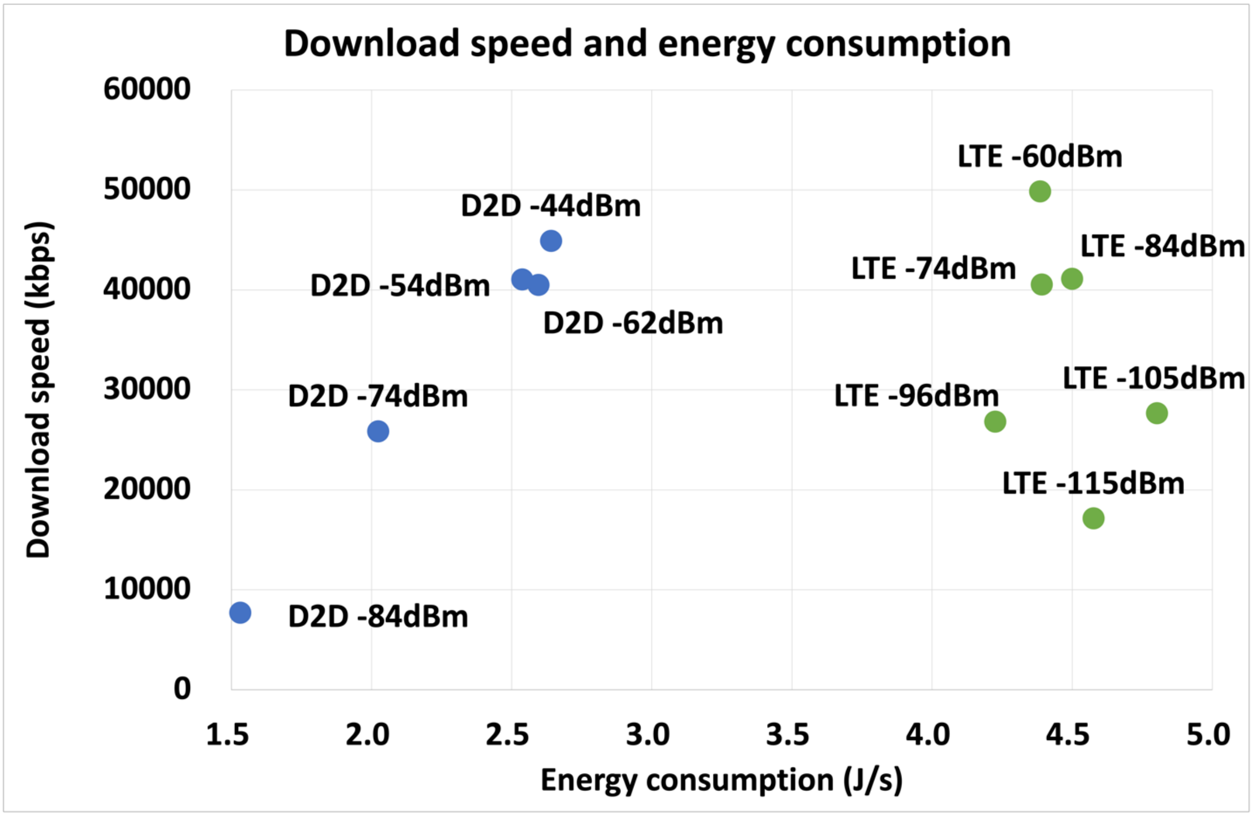

Figure 3-9 Relation for download speed and energy consumption in LTE and D2D

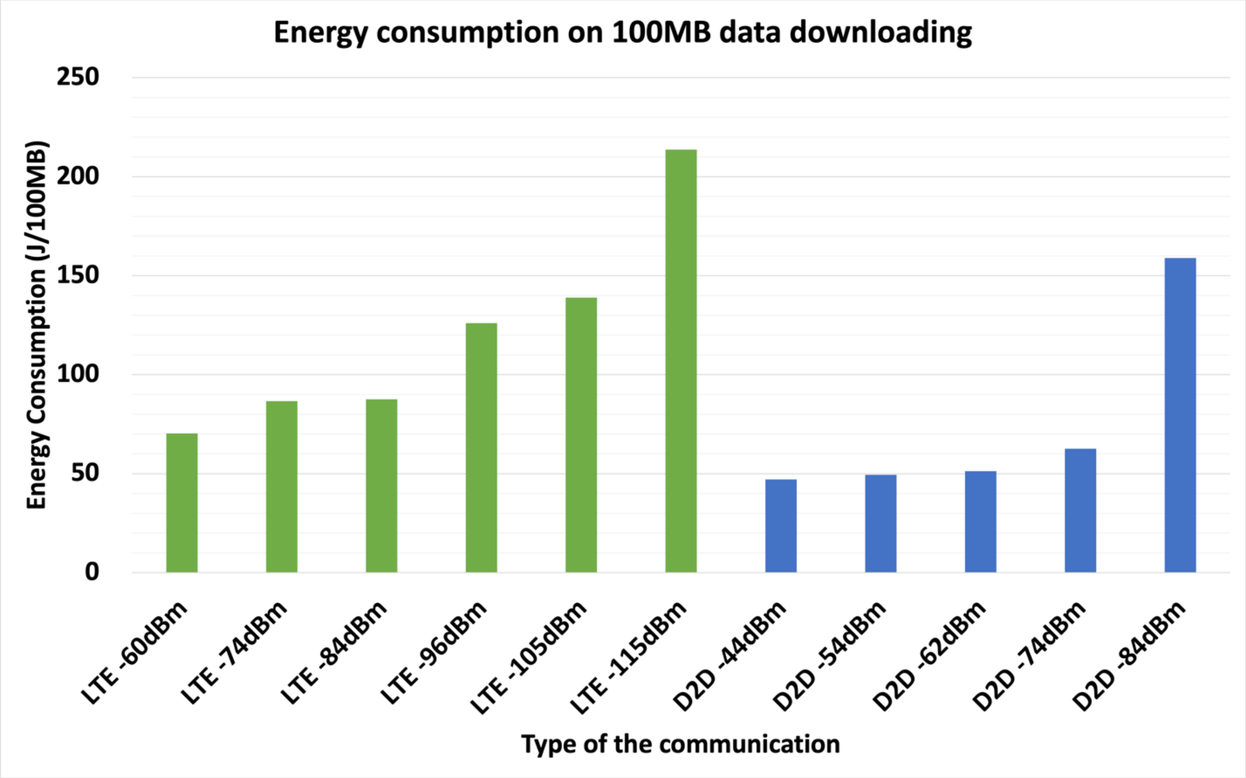

Figure 3-10 The energy when downloading 100 MB of data using D2D and LTE

Fig. 3-11 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 3.2.4 can be set to -74dBm as an example in this case.

Figs. 3-7, 3-8, and 3-9 show the raw data of the experiment, and Fig. 3-10 and 3-11 show the results of the analysis calculated by combining the results of Figs. 3-7, 3-8, and 3-9. Fig. 3-7 indicates that -96dBm in LTE consumes less energy than other

RSSIs. However, in Fig. 3-8, 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. 3-7, -96 dBm appears to consume less energy than the other RSSIs.

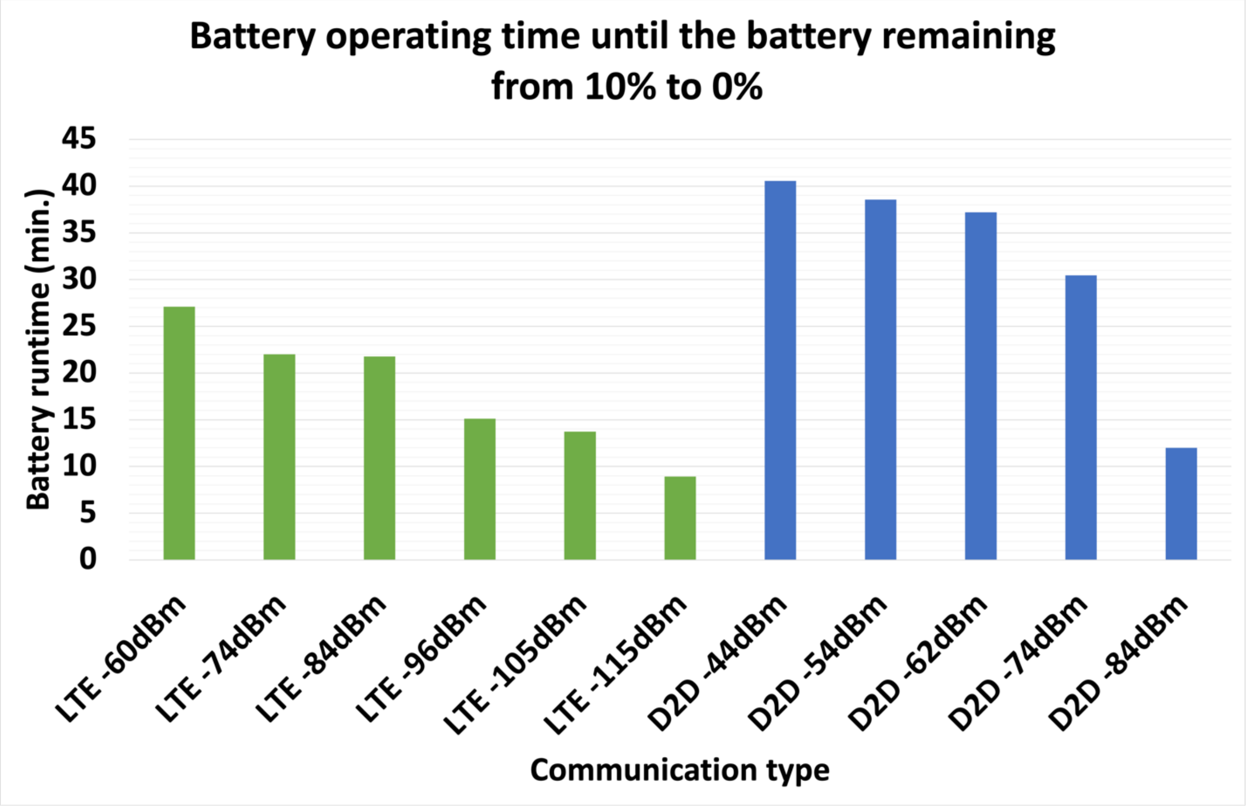

Figure 3-11. Battery operating time until the battery remaining 10% to 0% (download 100MB every 30 s)

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. 3-10. The same applies to – -105dBm. According to Fig. 3-8, the download speed is faster than – -96dBm. However, according to Fig. 3-10, 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. 3-9 shows the resulting relationship; it is expected that a signal strength, RSSI greater than D2D -74 dBm will lead to an extended battery operation. From Fig. 3-12, 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.

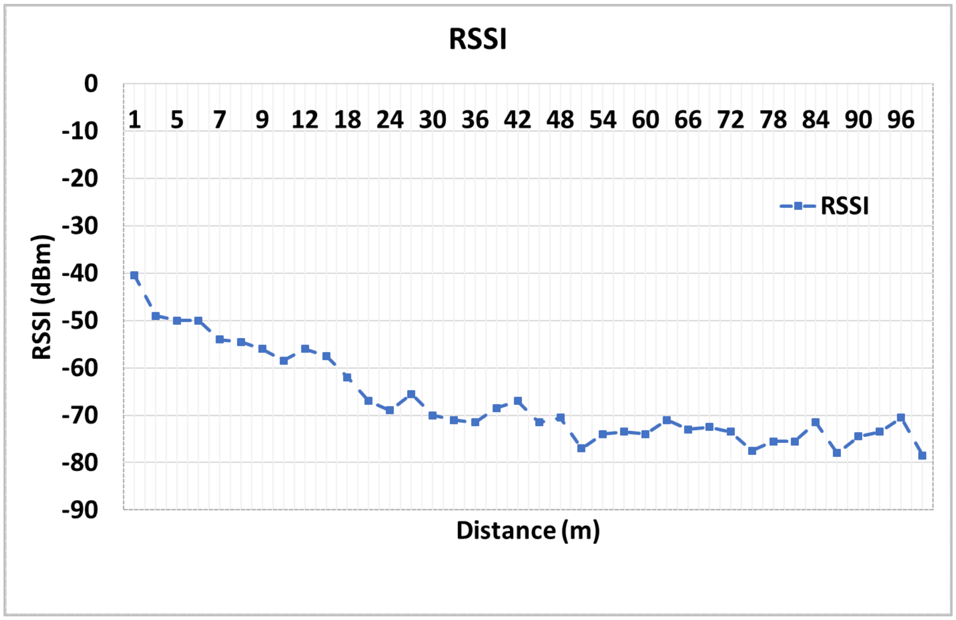

Figure 3-12 Relation of the distance and RSSI of D2D

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. 3-13 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.

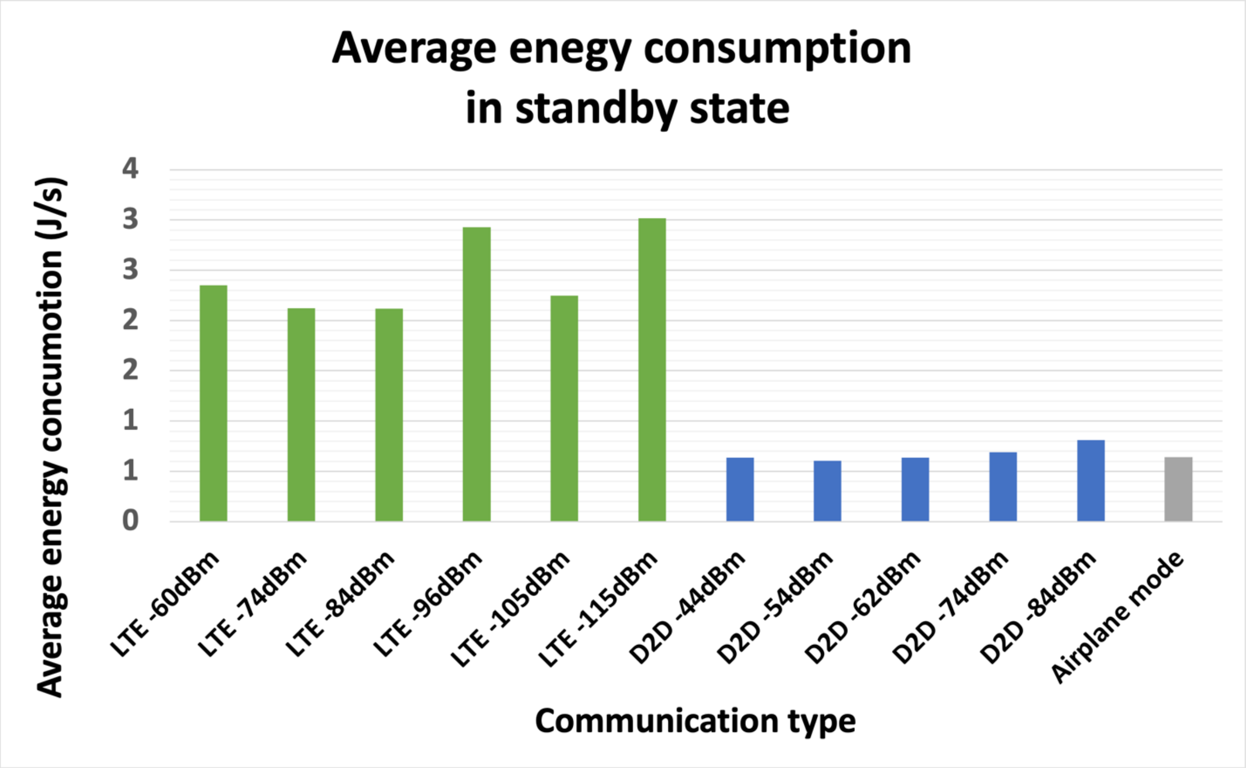

Figure 3-13 Average energy consumption in standby state

3.3.3Model 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.3-6 and the system model as shown the Fig.3-2. The parameters are as below and can be shown by the equation 1.

PEB: Probability of execute EB
ECTOT_B-UE: Total energy consumption
ßD2D-idle: Energy consumption of idle of D2D
ß5G-idle: Energy consumption of idle of 5G
V: Voltage
I: Current

$$\begin{aligned} EC_{\mathrm{Total}_{\mathrm{B-UE}}} = P_{EB}\left[\beta_{\mathrm{D2D-idle}} + \left\{\int_{t_{D2D-start}}^{t_{D2D-end}} V\,(t_{D2D}) \times I(t_{D2D})dt\right\}\right] \\ +(1-P_{EB})\left[\beta_{\mathrm{5G-idle}} + \left\{\int_{t_{5G-start}}^{t_{5G-end}} V\,(t_{5G}) \times I(t_{5G})dt\right\}\right] \end{aligned} \tag{3.1}$$

scheme based on the result of the measurement experiment as shown the Fig.3-6 and the system model as shown the Fig.3-2. The parameters are as below and can be shown by the equation 3.1.

3.4 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 3-14. In this way, we confirmed the effectiveness of our scheme in various environments. The experimental method was the same as described in Section 3.3, measuring the average power consumption during data download. In the experiment in Section 3.3, we reproduced the reception strength of the base station and D2D by using an anechoic chamber to check the relationship between download speed 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 3-15 shows the energy consumption J/Second 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 3-16 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 3-18 shows the results calculated by analyzing the measurement results in Figures 3-16 and 3-17. It shows a comparison of the power consumption J when 100 MB 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.

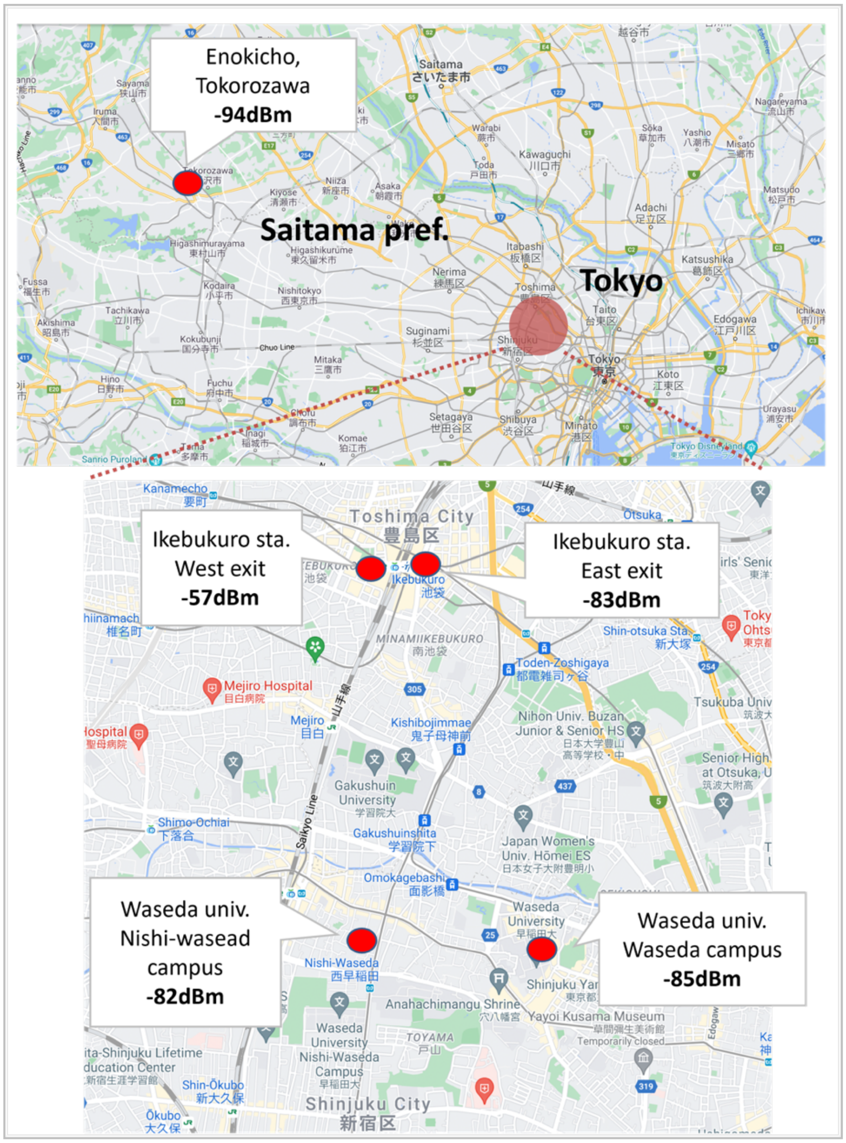

Figure 3-14 Map for the experiment point

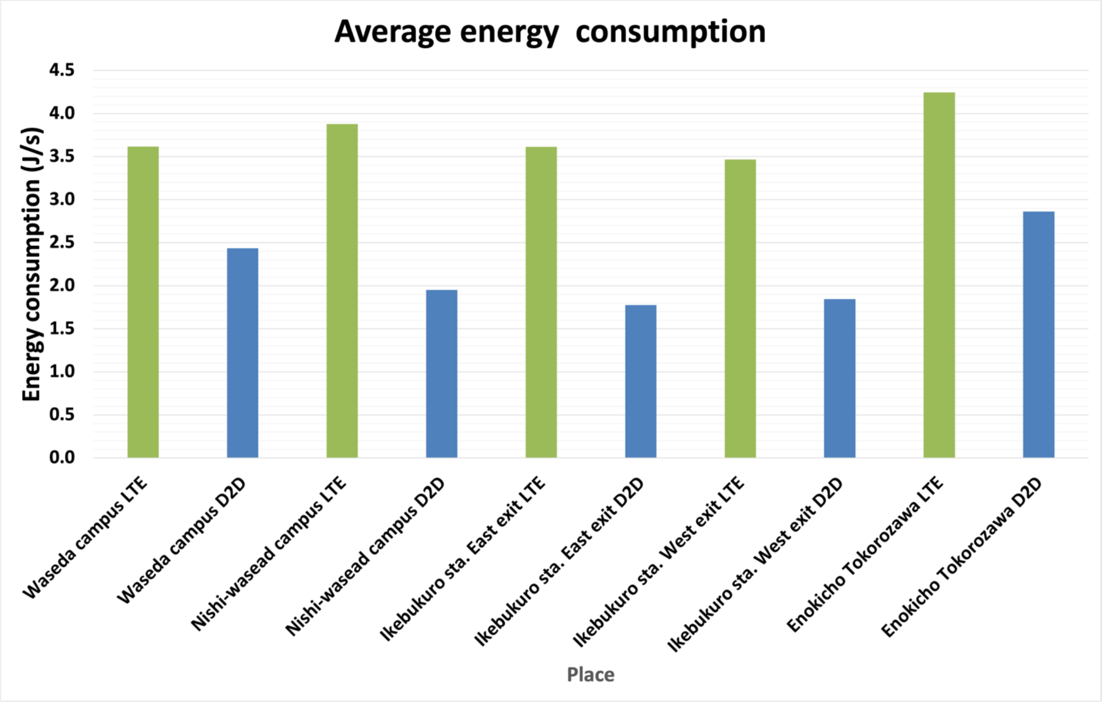

Figure 3-15 Average energy consumption at each location

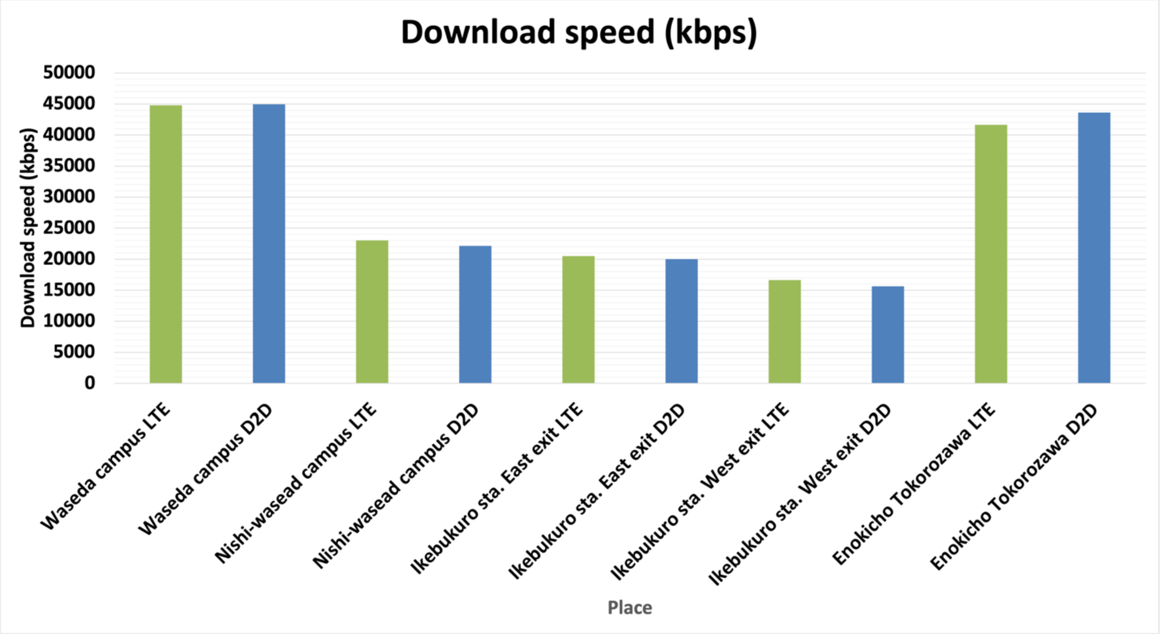

Figure 3-16 Average download speed at each location

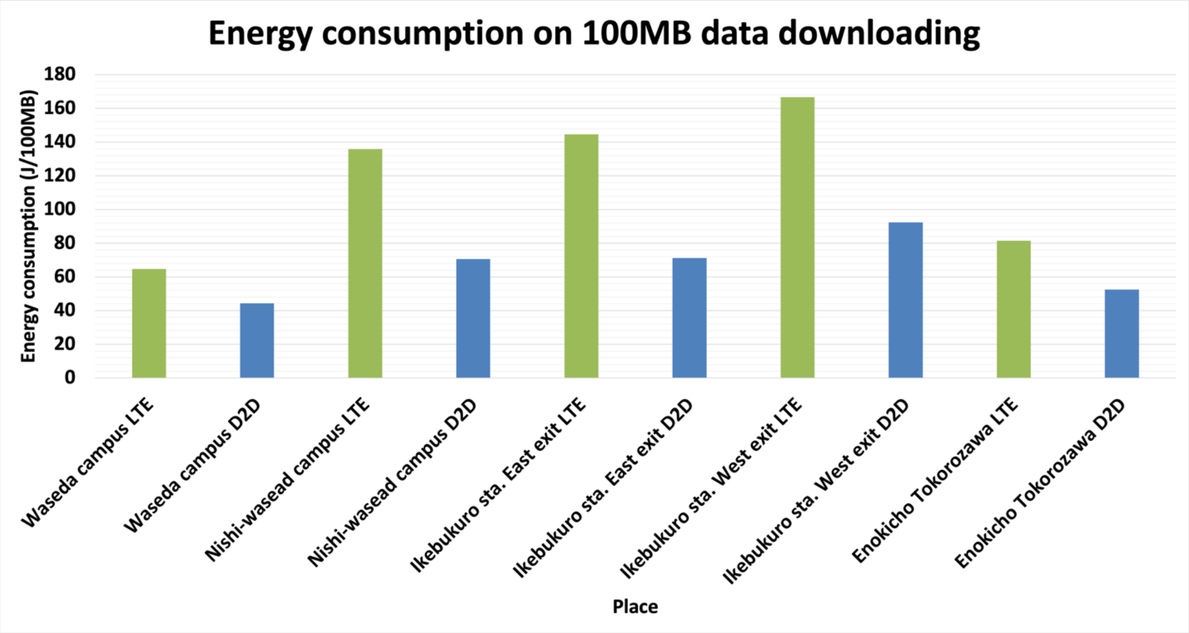

Figure 3-17. Energy consumption on 100MB at each location

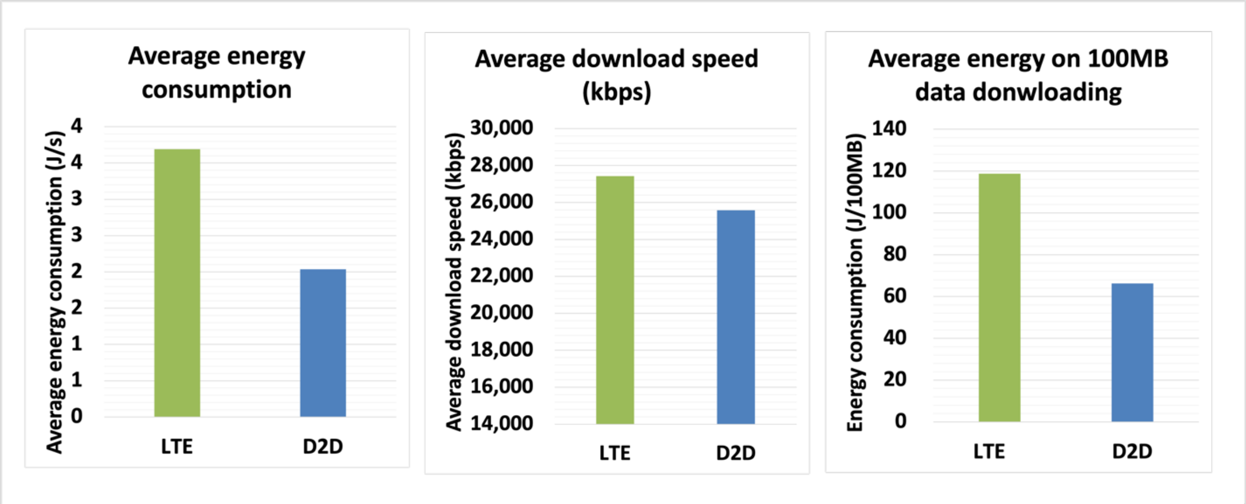

Figure 3-18 The average value of all locations

3.5 Simulation Study

The results and values of the measurement study introduced in above 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 here. In addition, this comparison is based on the experimental results obtained in above, and we recognize that the results are realistic and concrete. And, Matlab is used for the simulation tool.

3.5.1Simulation 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 train was chosen as the scene where smartphones are used on a daily basis. As a result of a survey of 500 men and women who commute by train, 93.8% of them answered that they use smartphones.[45] 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 [46].
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 MB 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 3-19 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; $EC_{B\text{-}UE\text{-}TOT}=EC_{EBTOT}+EC_{LTETOT}$, the total energy consumption of B-UE, $EC_{B\text{-}UE\text{-}TOT}$ 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 3.3 is used. Therefore, when 100 MB is downloaded in a single instance of communication, energy consumption occurs, as illustrated in Fig. 3-10, 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. 3-12. In addition, as confirmed in Figure 3-11, 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.

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 3-1 lists the simulation parameters. This table summarizes the simulation environments and scenarios described above. As shown in Table 3-1, the battery capacity is 2800 mAh under the same conditions as the experimental smartphone in our simulation study.

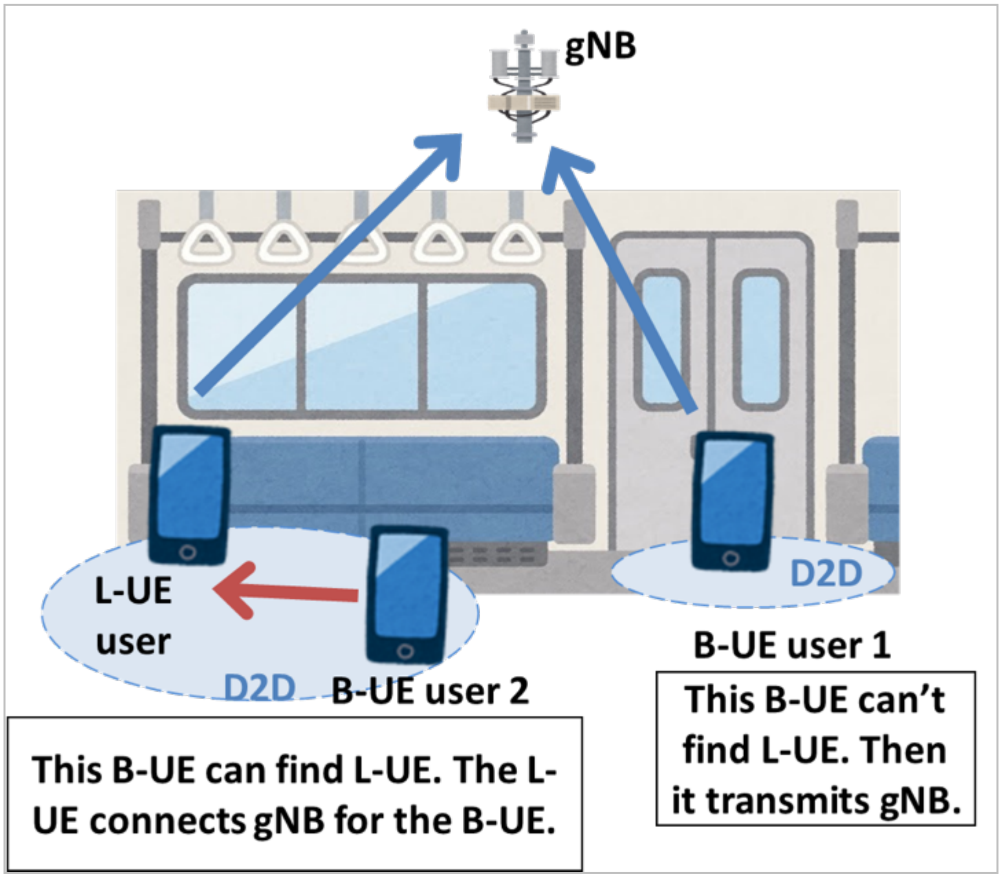

Figure 3-19 Simulation scenario and environment.

3.5.2 Simulation Results

The simulation results are shown in Fig. 3-20. 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.

Table 3-1 Simulation scenario parameters

Parameters (scenario)	Value or Explanation
The number of UE	Vehicle occupancy = 50% (77 UE, that means 77 users)
LTE quality RSRQ	-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 MB
Battery remaining of L-UE (%)	10 %

Table 3-2The 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%

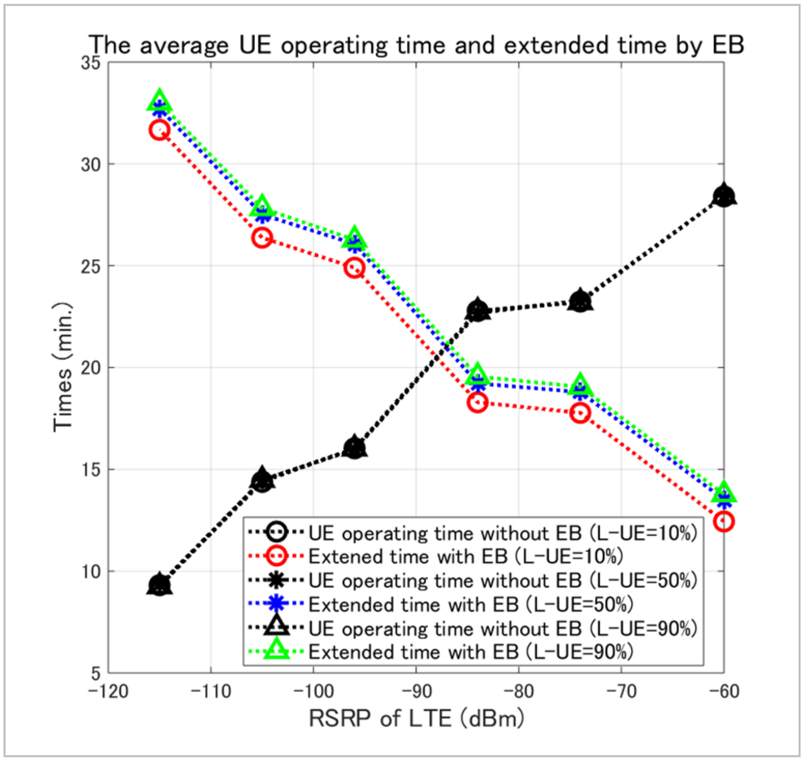

Figure 3-20 Average service operating time and the extended time by EB (10%~90% L-UE in all UEs)

Accordingly, all the black lines overlap. Without the black 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 3.3. From the black lines in Fig. 3-20, we can see 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 see that the EB can extend the UE service operating time at any RSRP of LTE. 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.3-20, 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. 3-20) and extended time with EB (each red, blue, or green color point in Fig.3-20). 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. 3-12, 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 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 II shows the battery extension rate. This ratio is the UE extended service operating time ratio by EB based on the simulation results Fig. 3-20. 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 %.

3.6 Summary

This study 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 3.3 and 3.5, 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 3.5 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.

Chapter 4

Energy Burden and Fairness Evaluation of Energy Borrowing Transmission Scheme

4.1 Introduction

In this chapter, we extend the "Energy Borrowing Transmission Scheme" described in the previous chapter to a method that considers the power burden and fairness of the terminals to which power is lent. In the previous chapter, we designed and proposed a basic concept, system model, including communication protocols for the power-lending scheme. However, because these are basic protocols, they do not focus on the power burden of the lender. In addition, if there are multiple lenders, fairness is not considered. It is important to consider the lender when considering an actual system. Therefore, in this chapter, we propose to control the L-UE burden by setting an upper limit on the power to be lent. We also propose a mechanism in which the maximum limit is reached and the terminal is not lent for a certain period of time, thereby allowing multiple terminals to take turns lending power to each other. This is expected to ensure fairness because multiple L-UE terminals will lend a small amount of L-UE.

4.1.1Related Works

The proposal in this chapter is an extension of that in the previous chapter.[47] In the previous chapter, when a B-UE chooses an L-UE, three threshold values are set as decision criteria: RSSI of D2D communication, CQI of cellular communication, and remaining battery capacity of the L-UE. In other words, if the L-UE has a remaining battery capacity above the threshold, it would lend its own battery. To minimize the power consumption of B-UE, L-UE was selected as the terminal with the strongest D2D communication RSSI among those that exceeded the three aforementioned threshold values.However, this selection method may result in a concentration of requests for terminals in certain good conditions. In addition, the concentration of requests on a particular terminal increases the burden on that terminal and impairs fairness. We propose a selection method that reduces the power burden by setting an upper limit on the loaned power, thereby extending the operating time of the borrowed terminal.

4.1.2Contribution

Instead of focusing solely on terminals that borrow power, this study focused on L-UEs, which are terminals that lend battery resources, and proposed a novel terminal selection method that considers the burden on the L-UE remaining battery power and fairness with surrounding terminals. The method described in the previous chapter adopted the same indicators for both B-UE and L-UE, resulting in redundancy in the terminal selection. Therefore, the proposed method eliminates redundancy and enables an efficient selection. In addition, we incorporated an operation in the L-UE that makes a decision based on the total power lent per day and the power lent by the currently connected B-UE. This makes it possible to lend battery resources while considering the power burden on the L-UE.

To verify the effectiveness of the proposed method, we conducted measurement experiments using actual equipment to determine (1) the power consumption during communication with base stations, (2) the power consumption of B-UEs, and (3) the power consumption of L-UEs.

Thereafter, we verified the battery extension effect and fairness of the proposed scheme via simulation analysis.

The contributions of this chapter are summarized below:

- By integrating a lending upper limit into the scheme, focusing on the power burden of L-UEs, and including a lending upper limit in the selection criteria for L-UEs, more appropriate terminal selection can be made.
- By introducing an upper limit, a situation in which a burden is placed on a particular terminal can be avoided.

- The upper limit also makes it possible to take turns lending power to other terminals in the vicinity.
- The previous chapter exhibited redundancy in the terminal selection method; hence, we improved the efficiency of the selection method by improving the selection criteria.
- The power consumption of the cellular, B-UE, and L-UE was clarified via experiments, and further simulations were conducted to clarify the fairness effect of this method, including the effect of extending the battery life of the B-UE.

4.2 System Model

4.2.1 Protocol of the Energy Borrowing Transmission Scheme Considering Power Burden in Power-Lending

The fundamental protocol of the energy-borrowing transmission scheme is illustrated in Fig. 4-1. In this study, the communication protocol is designed with reference to prior works [47]; it is based on the LTE system, but the basic concepts and flow remain the same for 5G. Therefore, it is also expected to be applicable to 5G systems.

1. The terminal at the top of the figure has low battery power and would like to extend the battery life. In this case, it enters the energy-borrowing (EB) mode and becomes a B-UE.
2. B-UE sets the connection state with 5G to the RRC_ inactive state. By setting this state, the base station and core network side will maintain the terminal response; however, the terminal side will enter a mode similar to standby, thus reducing the power consumption. [38]

The objective of this research is to reduce the battery drain and increase the battery running time using D2D communication; the UE communicates with the base station as little as possible. Therefore, during EB communication, B-UE is designed to always use the RRC_inactive mode for communication with the base station. This allows the B-UE to reduce power consumption by going into the standby mode.

3. When a communication request occurs on the B-UE, the B-UE turns on Wi-Fi. The B-UE then searches to determine whether there is an L-UE, a candidate for a cooperative terminal, within its Wi-Fi communication range. B-UE broadcasts a request for cooperation in power borrowing and lending using Wi-Fi, which is the detection and establishing connection process in the figure.
4. The B-UE detects the L-UE because it is a cooperating UE and is in Energy Lending mode, in which it lends its own battery resources to other terminals. The L-UE responds to a B-UE communication request. In this system, there are two types of L-UEs: "L-UE candidate," which is a candidate for L-UE, and "L-UE," which has established D2D connection with the B-UE. However, for simplicity, they are collectively referred to as L-UEs here, and a detailed explanation is provided later.
5. B-UE establishes a D2D connection with the L-UE by using Wi-Fi. This was the establishment of an energy-borrowing session. The detection and establishment connection process is presented in Fig. 4-1.
6. The L-UE communicates with the base station on behalf of the B-UE, receives the uplink data of the B-UE via D2D, and forwards it to the base station. It also receives downlink data from the base station via 5G and forwards it to B-UE using D2D. This is the exciting EB in Fig. 4-1. The session is maintained provided certain conditions are met, and data continue to be exchanged on both the uplink and downlink.
7. When the power borrowing and lending scheme is terminated, the B-UE declares the end of the energy-borrowing transmission, and the D2D communication is terminated. This marks the end of the EB session. There are

several conditions for the termination of the EB session, such as when no communication is performed for a certain period of time, when the power lent by the L-UE to the B-UE exceeds the upper limit, as described below, when the D2D communication status deteriorates owing to movement and falls below the RSSI threshold, or when the L-UE's power is lent by the B-UE to the L-UE. This includes the case in which the communication quality of the L-UE link to the base station deteriorates, and the CQI threshold falls below the CQI threshold.

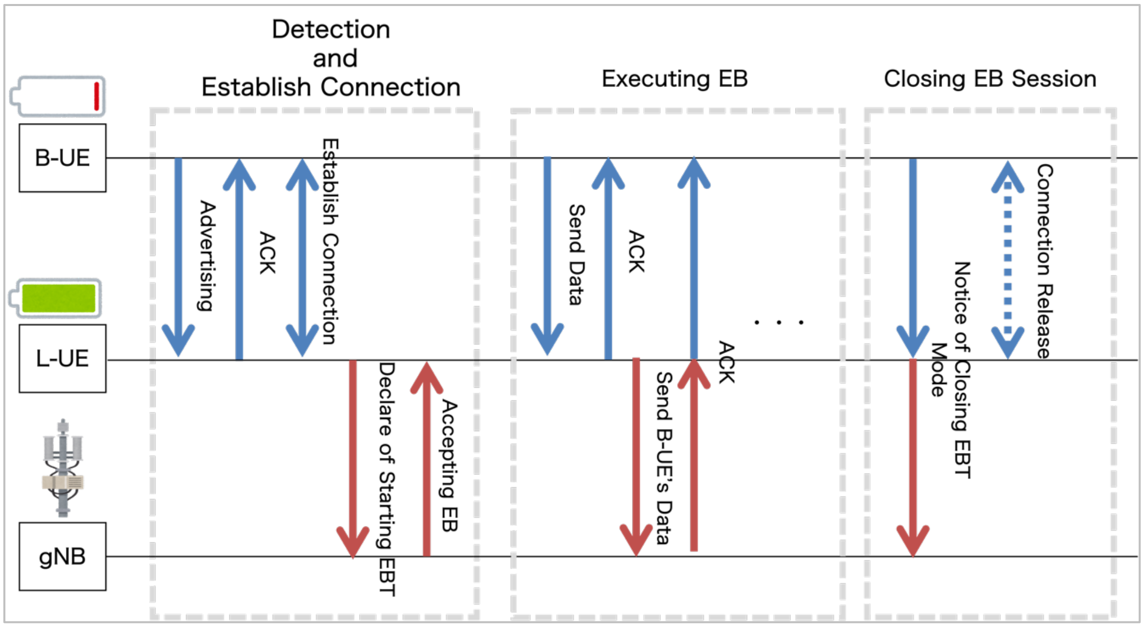

Figure 4-1 Basic flow of the energy-borrowing transmission scheme

4.2.2 Selection Protocol of L-UE

In the detection and establishment connection in Fig. 4-1, the B-UE searches and selects an L-UE in the following flow to initiate the energy-borrowing scheme.

Flow of B-UE's L-UE search and selection

1. When a communication request occurs, the B-UE broadcasts a request for cooperation in borrowing energy to the surrounding area using Wi-Fi.
2. If an L-UE candidate exists, the B-UE receives a response from the L-UE candidate, and the terminal with the strongest received signal strength indicator (RSSI), which is the reception strength of D2D communication, among the responses from the L-UE candidate is designated as the L-UE. If there are no L-UE candidates, the B-UE communicates with the base station as usual.
3. Having determined the L-UE from the L-UE candidates, the B-UE starts energy-borrowing communication, in which the B-UE communicates with the L-UE while virtually using the L-UE's power.

The above flow is a more efficient version of the operational flow of the B-UE in a previous study, which is a basic study. The B-UE selects the terminal with the strongest RSSI among the L-UE candidate terminals as the L-UE for the following reasons. The experimental results of previous studies and this study demonstrate that there is a correlation between RSSI, which is the reception strength of D2D communication, and the power consumption generated by the communication; as it is known that communication can be performed with low-power consumption if RSSI is strong, the objective is to extend the terminal operating time of B-UE. In this study, the terminal with the strongest RSSI among the L-UE candidate terminals is selected. In a previous study, both the B-UE and L-UE set threshold values and made judgments to check whether the energy-borrowing scheme could be implemented, and only when the conditions were met was energy-borrowing communication initiated. The first is the RSSI value, which is the D2D reception strength that covers the strength of the D2D link between the B-UE and the L-UE candidate; the second is the channel quality indicator (CQI) value between the base station and the L-UE; the CQI value is the channel quality indicator between the base station and cell phone; and the third is the D2D link between the B-UE and L-UE, which indicates a measure of communication quality between terminals. The third is the remaining battery capacity of the L-UE.

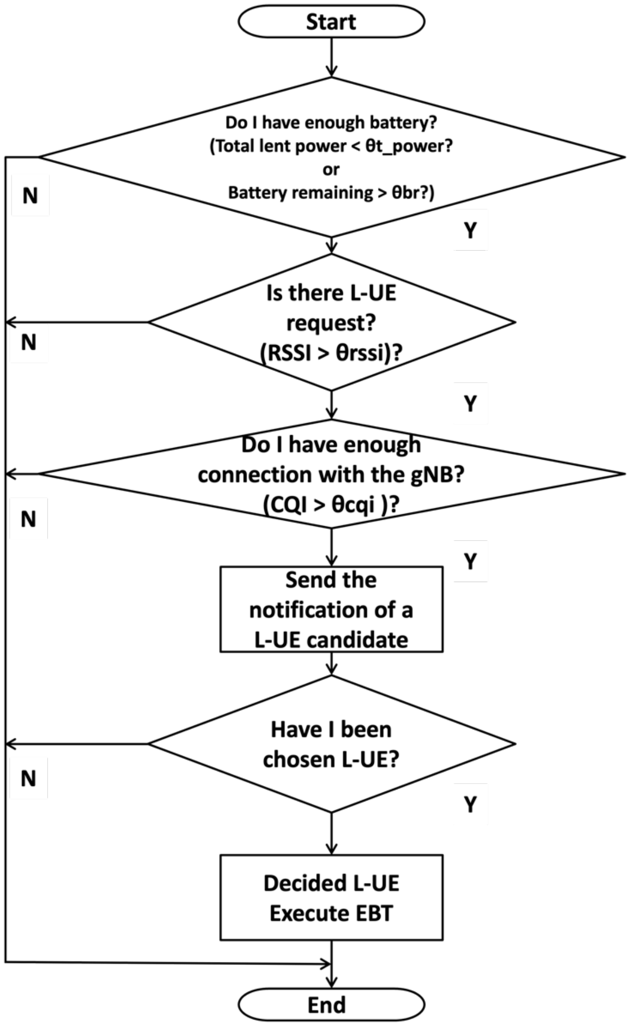

Figure 4-2 L-UE operation during the search and selection of L-UE

Each of the B-UE and L-UE has its own threshold value, and both parties determine whether energy-borrowing communication is possible. However, the decision by both B-UE and L-UE is considered redundant because it duplicates the decision. However, in this study, as demonstrated in the B-UE L-UE search and selection flow described above, the B-UE side only selects the one with the strongest RSSI value, and the judgment operation on the B-UE side is made more efficient. Instead, the L-UE side determines whether to lend battery resources and introduces a decision criterion that also considers the power burden on the L-UE. Accordingly, we developed a terminal selection method that reduces the power burden on the L-UE while making decisions more efficient. Figure 4-2 illustrates the L-UE flow. Figure 4-2 illustrates the flow of an L-UE candidate terminal responding to a B-UE communication request and lending its own station power as an L-UE.

Operation Flow of L-UE in Search and Selection

1. To determine whether a station is a candidate L-UE terminal, it first checks whether its remaining battery capacity and total power credit limit exceed the threshold values. The upper limit of the total power loan represents the total power lost to the B-UE within a 24-h period. If the remaining battery capacity is lower than the threshold value, the terminal itself does not have sufficient battery power. If the total power lending upper limit is higher than the threshold value, it implies that the terminal has already lent more power to the B-UE than the threshold value. These two values were assumed to be set arbitrarily by the user. For example, the threshold value of the remaining battery capacity can be expressed as 85%, and the upper limit of the total power lending is 5%. In other words, if the remaining battery charge falls below 84%, the power will not be lent to other terminals, and only 5% of the total power can be lent to other terminals per day. When the remaining battery capacity is lower than the threshold value, or when the total power lending upper limit is higher than the threshold value, the station will not participate in the scheme to prevent its own power consumption from being depleted. The flow proceeds to the next flow only if it does not terminate.
2. The L-UE receives an energy-borrowing cooperation request broadcast by the B-UE. At this point, the L-UE judges the received signal strength RSSI, and if it is lower than the threshold value, it judges that the D2D communication strength is weak and may be unable to communicate stably and terminate. If it is higher than the threshold value, it proceeds to the next step.

3. The L-UE checks communication quality with the base station. A CQI was adopted as an indicator for this check. If it is lower than the threshold value, the L-UE judges that the communication quality is insufficient and terminates the process. If it is higher than the threshold value, it proceeds to the next step.
4. The B-UE sends a "notification of an L-UE candidate" to the B-UE using the D2D.
5. If the B-UE is selected as an L-UE, the B-UE starts energy-borrowing communication as an L-UE; otherwise, communication is terminated.

Therefore, to become an L-UE candidate terminal, the following conditions must be satisfied:

$$L-UE\ candidate = Total\ lent\ power < \Theta\mathrm{t}\_power \quad \&\& \quad Battery\ remaining > \Theta\mathrm{br} \\ \&\& \quad RSSI > \Theta\mathrm{rssi}\ \&\&\ CQI > \Theta\mathrm{cqi}$$

4.2.3L-UE Operation During Energy Borrowing Transmission

During the energy-borrowing communication, the L-UE constantly records the power lent to other terminals. If the upper limit is exceeded, the energy-borrowing communication is terminated. Two indices are adopted in this case. The first is the upper limit of the total power loan, which is the upper limit of the percentage of power lost in a day, and is the conditional value described above in Section 4.2.2. Once the L-UE establishes a connection with the B-UE, the L-UE initiates energy borrowing communication and continues to lend power provided the set conditions are met. However, by setting an upper limit on the amount of power granted per session, it sets the upper limit for power lending in a single session. Both indicators are values for 100% battery, and the L-UE terminates energy-borrowing communication when these upper limits are exceeded.

The L-UE also constantly records the signal strength of D2D communication, 5G communication quality, remaining battery power of its own station, and communication time and terminates communication if any of these conditions are no longer met. The above operation is described using Figure 4-3.

Figure 4-3 illustrates the behavior of a running L-UE in energy-borrowing communication. This corresponds to the execution of the EB in Figure 4-2. The behavior of L-UE is explained based on the flow in Figure 4-3, the behavior of the L-UE is explained.

1. When the L-UE candidate is selected as the L-UE, it establishes an energy-borrowing session with the B-UE to initiate energy-borrowing communication.
2. During the energy borrowing communication, the L-UE determines the following
    a. Whether the D2D receives power above the threshold value.
    b. Whether the CQI is above the threshold value.
    c. The time without B-UE communication that does not exceed the threshold value.

   For a and b, if they are below the threshold values, it is ascertained that it is difficult to execute energy-borrowing communication, and the communication is terminated. If it is greater than the threshold value, it continues. For c, if there is no communication for a certain period, and communication is terminated to save energy.
3. The L-UE judges whether the power lent in the energy-borrowing communication of the currently connected session is less than the threshold value. If it is low, it continues. If it is higher than the threshold value, the maximum lost power in one session is exceeded, and the communication is terminated.
4. The L-UE should determine whether the total power lent in one day is less than or equal to the threshold value. If lower, it continues. If greater than the threshold value, the maximum power loaned in a day has been exceeded, and

the session is terminated. The L-UE candidate mode in energy borrowing mode shall be terminated until the next day, and the L-UE shall be set not to be a candidate for L-UE.

5. The L-UE checks the remaining battery power of its station. If it is below the threshold value, it continues. If it is greater than the threshold value, it determines that there are no resources available for loans to other terminals, and it then terminates. The L-UE candidate mode in the energy-borrowing mode is terminated, and the L-UE is set to not become a candidate for L-UE until the remaining battery charge exceeds the threshold value, for example, by recharging the battery.
6. If all the conditions from 2 to 5 are met and energy borrowing communication can be performed without any problem, the communication is successfully performed. In addition, the total amount of electricity loaned for the day, the amount of electricity loaned per connection, and the time of the last communication with the B-UE are recorded.
7. During the energy borrowing communication, steps 2 to 6 are repeated.

Hence, if the total power lending limit is exceeded, it is terminated, and the L-UE does not participate in energy borrowing communication for the entire day. However, if the upper limit of power lending per connection, which is the value of the percentage of power that can be lent per connection, is exceeded, it will not participate in energy borrowing communication for a certain period. If the maximum time limit is exceeded, the L-UE will again become a candidate for L-UE. This behavior prevents concentration on a single terminal and improves fairness by allowing the L-UE to borrow power slightly from its surroundings when there are multiple L-UEs in the vicinity.

Two types of power loan limits are used: a total power loan limit, which is a daily limit, and a per-connection power loan limit, which is a limit for each session in which an energy-borrowing connection is established, to prevent situations in which a particular L-UE is overloaded and the L-UE's own battery is depleted by excessively loaning battery resources to other terminals.

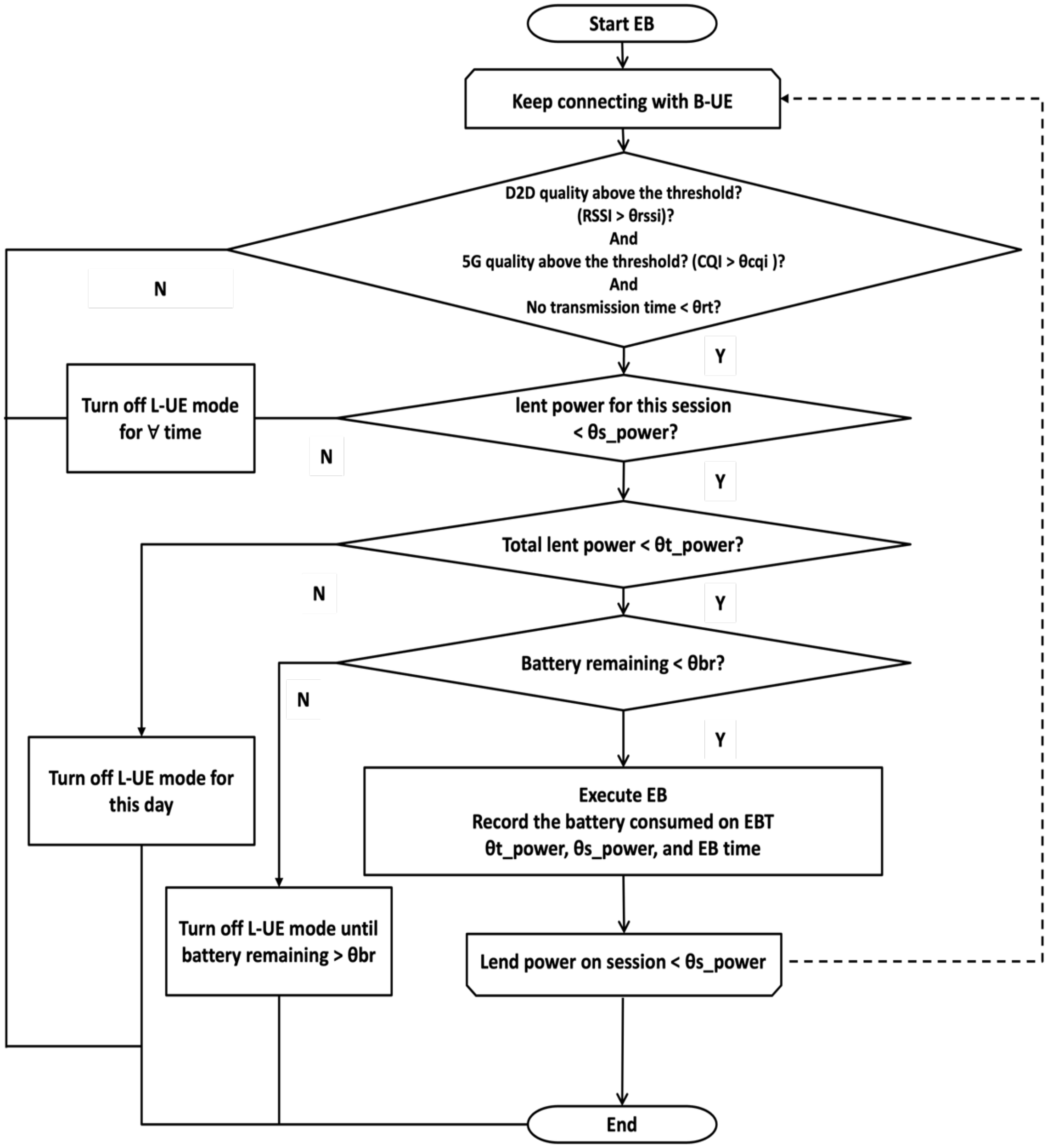

Figure 4-3 Operation flow of L-UE during executing EB when energy borrowing communication is executed

4.3 Experiment

4.3.1 Overview of the Experiment

To clarify the power saving and battery life extension effect of B-UE and power burden of L-UE in the proposed system, measurement experiments were conducted using actual equipment. The power consumption of the B-UE and L-UE was also measured and analyzed in this study to verify the power burden on the L-UE. The device utilized for the experiment was a Samsung Galaxy S5 ACTIVE SC-02G [43]. LTE was adopted for cellular communication, and Wi-Fi tethering with IEEE802.11 was used for D2D communication. In the experiment, the tethering parent device served as the L-UE while the tethering child device served as the B-UE. The TEYGLE POWER BENCH by TRYGLE was adopted for these measurements [44]. The electric current was measured by attaching a TEYGLE POWER BENCH to the positive terminal of the battery of the mobile terminal. The TEYGLE Prosess Logger can be installed on a portable terminal to acquire and record logs of battery voltage, CPU usage, and the amount of data transmitted and received in actual time. The current and voltage reveal the power consumption W, and the amount of data transmission is measured simultaneously to check the power consumption during the communication. The experiment was conducted using LTE-enabled smartphones. This was because the LTE environment was the only option available at the time of the experiment. However, in terms of the comparison between cellular and D2D communication, the outcome of the comparison is the same, and it can be deduced that there are no problems in the evaluation of the method.

The measurement procedure is summarized as follows.

1. Upload a 2.56 GB video file to an online storage beforehand.
2. Download the file in 1, then acquire and record the power consumption of the mobile terminal and the amount of data being communicated in actual time during the download.

3. After the measurement, analyze the download speed (kbps) during the download and obtain the power consumption (W) from the current and voltage to obtain the power consumption per data volume.

The measurements were performed on three targets: 1) LTE communication at one station without D2D (without using the proposed method), 2) B-UE (terminal borrowing power, tethered child unit), and 3) L-UE (terminal lending power, tethered parent unit). In the experiment, an anechoic chamber was used to reproduce the environment of each signal strength and clarify the trend of power consumption according to communication status. RSSI, which is the reception strength of D2D between B-UE and L-UE, was reproduced by adjusting the distance between the Wi-Fi tethering parent and child devices and installing them. The RSRP, which is the reception strength of the LTE signal, was reproduced by placing the unit near a door close to an outdoor environment, for easy reception of the LTE signal; conversely, the unit was placed in an anechoic chamber for poor reception. For RSSI, the D2D signal strength, the measurements were made of RSSI-30, -40, -50, -60, and -70 dBm when the RSRP was -65; RSSI-30, -40, -50, -60, and -70 dBm when the RSRP was -85; in addition, -60, -70 dBm were reproduced in a total of 15 patterns. The intensities reproduced in the experiment are presented in Table 4-1.

In a previous study, the reproduced receive strengths were -60, -74, -84, -96, -105, and-115 dBm for LTE communications. In D2D, when the RSRP of the tethered parent L-UE was -62 dBm, the RSRPs were -44, -54, -62, -74, and -84 dBm. Therefore, we solely verified the power consumption trend when the L-UE exhibited one RSRP-type. Based on this previous study, we comprehensively examined the power consumption trends by the L-UE reception strength in this study. In addition, as mentioned above, the previous study only verified power consumption during LTE communication and B-UE; hence, this study examines three types of L-UE: LTE communication, B-UE, and L-UE.

Table 4-1 List of received intensities reproduced in the experiment

LTE	L-UE	B-UE
RSRP -65dBm	LTE RSRP -65 dBm D2D RSSI -30, -40, -50, -60, -70dBm	LTE RSRP -65 dBm D2D RSSI -30, -40, -50, -60, -70dBm
RSRP -85dBm	LTE RSRP -85 dBm D2D RSSI -30, -40, -50, -60, -70dBm	LTE RSRP -85 dBm D2D RSSI -30, -40, -50, -60, -70dBm
RSRP -105dBm	LTE RSRP -105 dBm D2D RSSI -30, -40, -50, -60, -70dBm	LTE RSRP -105 dBm D2D RSSI -30, -40, -50, -60, -70dBm

4.3.2Experimental Result

Figure 4-4 shows the power consumption when 100 MB is acquired by the home station without using the method and the power consumption (J) when 100 MB is acquired by the B-UE. The gray bar graph shows the power consumption when communicating with the base station at the home station without using D2D. Therefore, it is not borrowing or lending power, but downloading to its own station. The gray bars show the power consumption when downloading at LTE reception strengths of RSRP-65, -85, and -105 dBm, from left to right.

On the other hand, the red, blue, and green bar graphs show the power consumption of the B-UE when 100 MB were acquired. The red bars show the power consumption of L-UE when its RSRP is -65 dBm and RSSI is -30, -40, -50, and -70 dBm, respectively. The blue bars show the power consumption when the RSSI is -30, -40, -50, and -70 dBm when the RSRP of the L-UE is -85 dBm, respectively. The green bars show the power consumption of the L-UE at an RSSI of -30, -40, -50, and -70 dBm when the RSRP is -105 dBm, respectively, compared to the power consumption when using the base station shown in gray for all intensities of RSRP-65, -85, and -105 dBm. It can be confirmed that the power consumption when using D2D, shown in red, blue and green, is lower. The power consumption tends to increase as the reception strength of

D2D becomes weaker, but in this experiment, even at -70 dBm, the weakest state of D2D, the power consumption was lower than that of the base station.

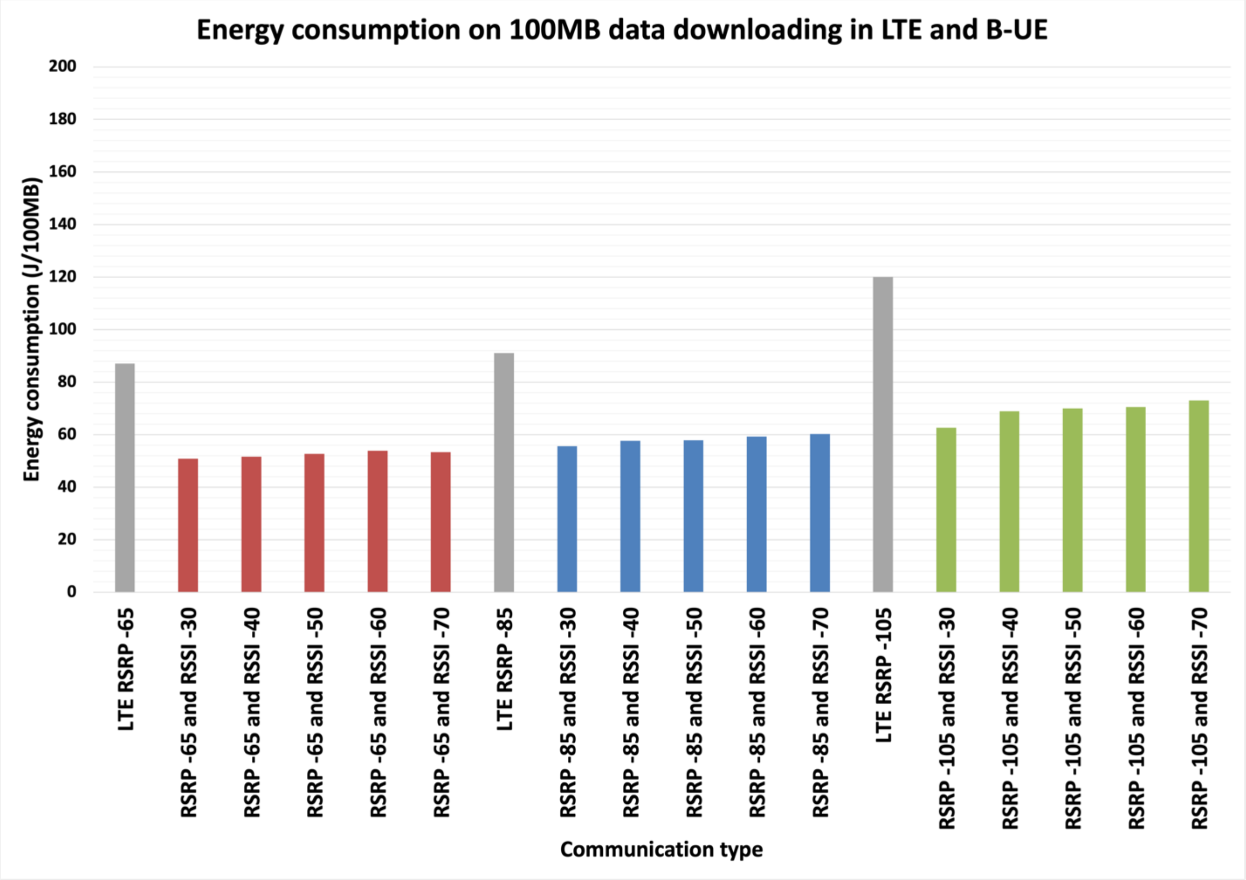

Figure 4-4 Power consumption when acquiring 100 MB in LTE without using the proposed scheme and the Power consumption of B-UE when 100 MB is acquired using the proposed scheme

Figure 4-5 also shows the power consumption in the L-UE when the B-UE acquires 100 MB. As in Figure 4-4, the gray graph shows the power consumption when data is downloaded at the own station. On the other hand, the red, blue and green bar graphs show the power consumption of the L-UE, respectively. The red shows the power consumption when the L-UE's RSRP is -65 dBm and RSSI is -30, -40, -50, or -70 dBm; the blue shows the power consumption when the L-UE's RSRP is -85 and RSSI is -30, -40, -50, or -70 dBm; the green shows the power consumption when the L-UE's RSRP is -105 dBm and The power consumption of LTE at -65, -85, and -105dBm is higher than the power consumption generated by the own station's communication, which is shown in gray, when the own battery resources are shared with other terminals using D2D. The results of this study confirm this. It can also be confirmed that, as with the B-UE, the power consumption increases as the reception strength of D2D communication becomes weaker.

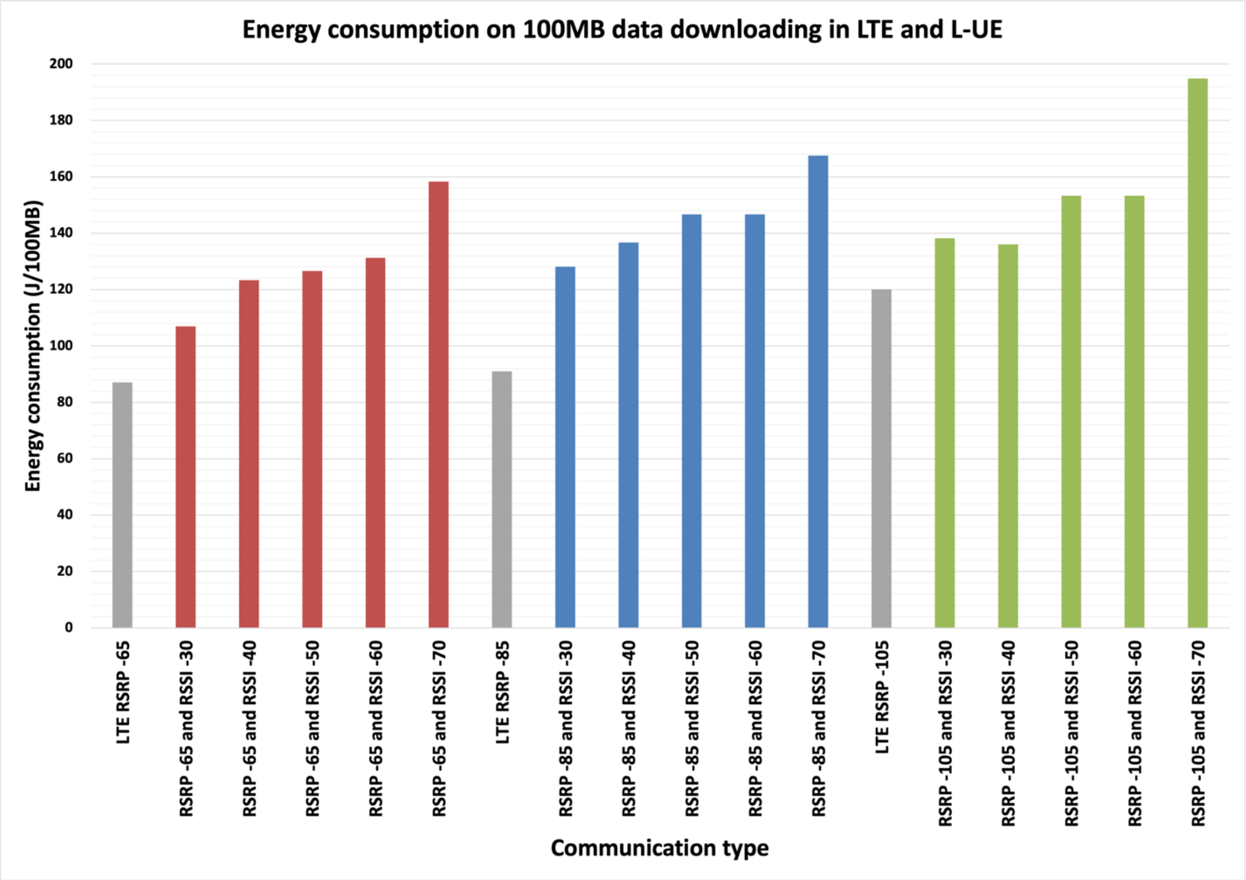

Figure 4-5 Power consumption when acquiring 100 MB in LTE without using the proposed scheme and the Power consumption of L-UE when 100 MB is acquired using the proposed scheme

Next, the experimental results were used to verify the battery life of the terminals. Figure 4-6 shows the run time when a terminal with 10% remaining battery power continued to download 100 MB of data once every 45 seconds until the battery ran out. The gray bar graph shows the run time when the terminal did not use D2D and downloaded the data by accessing the base station at its own station. From left to right, they show the drive time when the RSRP is -65, -85, and -105 dBm, respectively. The red, blue, and green graphs also show the battery run time for B-UE. The red represents the drive time of the B-UE when the L-UE RSRP is -65 dBm and RSSI is -30, -40, -50, or -70 dBm, the blue represents the drive time of the B-UE when the L-UE RSRP is -85 and RSSI is -30, -40, -50, or -70 dBm, the green represents the drive time of the B-UE when the L-UE RSRP is -105 The B-UE drive times are shown for RSSI at -30, -40, -50, and -70 dBm at dBm. From this figure, it can be confirmed that at all intensities, the battery runtime can be extended by using D2D to communicate with other terminals while virtually borrowing power from them rather than communicating with the base station to download the data.

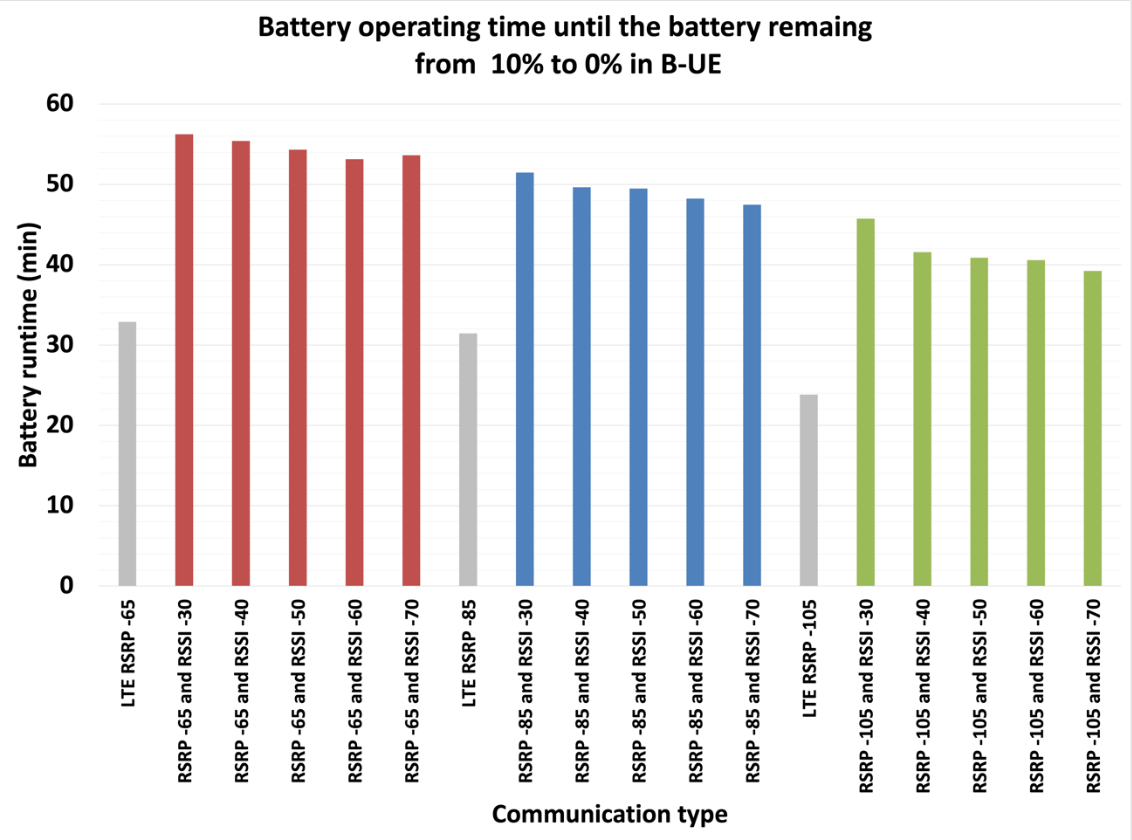

Figure 4-6 Battery life when B-UE with 10% battery remaining downloads 100MB of data once every 45 seconds

Figure 4-7 shows the drive time under similar conditions when a terminal with 10% remaining battery power continues to download 100 MB of data once every 45 seconds until the battery runs out. The gray bar graph shows the drive time when downloading is performed by accessing the base station at the terminal's own station without using D2D. The red, blue and green bars indicate the L-UE's operating time when the L-UE's RSRP is -65, -85, and -105, respectively, using D2D. Since the L-UE is the one that lends its own power, the L-UE does not need to use D2D to download data. It can be confirmed that the drive time is shorter than accessing the base station for downloading.

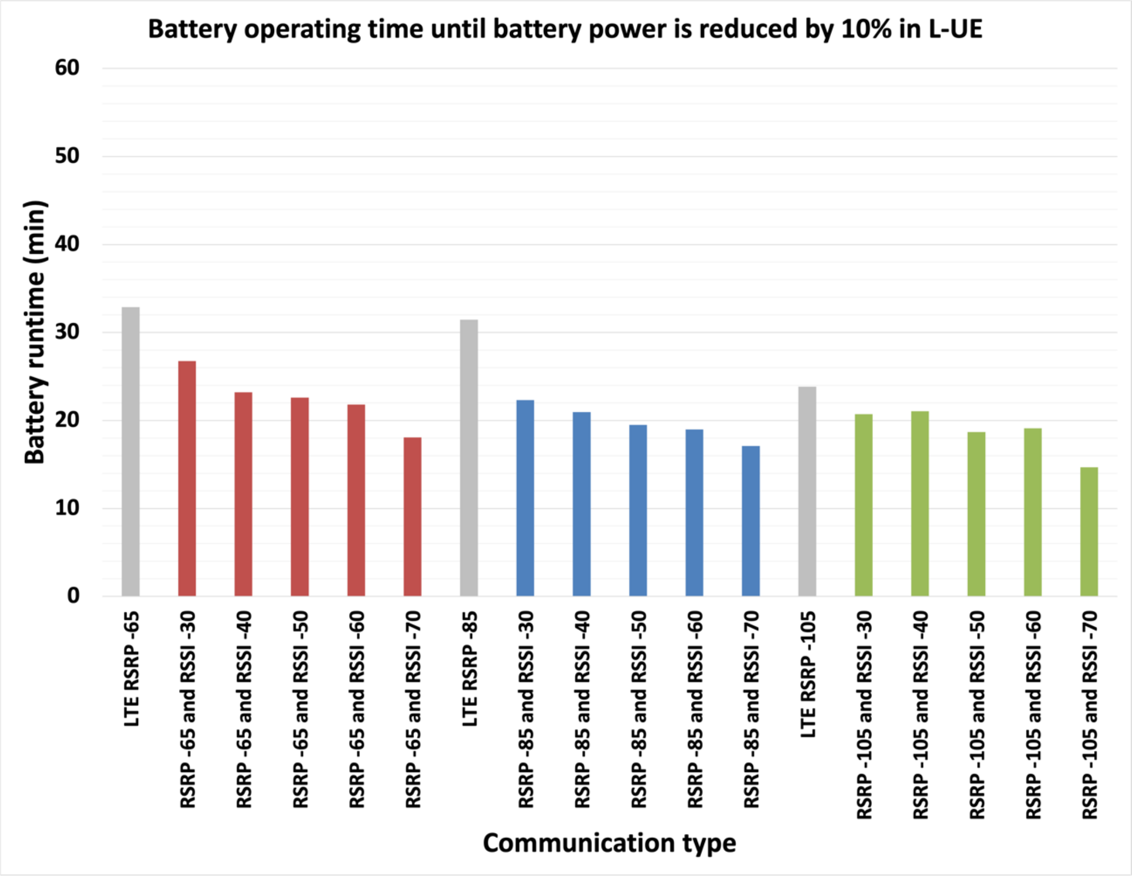

Figure 4-7 When L-UE downloads 100MB of data once every 45 seconds Time until B-UE's battery power is reduced by 10%.

Based on the results shown in Figures 4-6, 4-7, Figure 4-8 shows the rate of change occurs in the driving time of B-UEs and L-UEs by participating in the proposed scheme. The gray bar graph shows the drive time when the B-UE and L-UE do not participate in the scheme and communicate at their own stations, and this is used as the base value, which is 100%. From left to right, they represent the drive time at RSRP -65, -85, and -105. The pink bar chart shows the percentage change in drive time of B-UE when the RSRP of L-UE is -65 dBm. The red bar graph shows the drive time change rate of L-UE in %. All of them are the rate of change when RSSI is -30, -40, -50, -60, and -70 from left to right. The pink bars indicate that the battery runtime change rate for B-UE is approximately 160-170%, and this result confirms that B-UE can extend battery runtime by 160-170% by using the method. On the other hand, the battery drive change rate of L-UE, indicated by the red bar graph, is about 50-80%, and this result shows that the L-UE can extend its battery life by about 50-80% by participating in the scheme and lending its battery resources to other terminals.

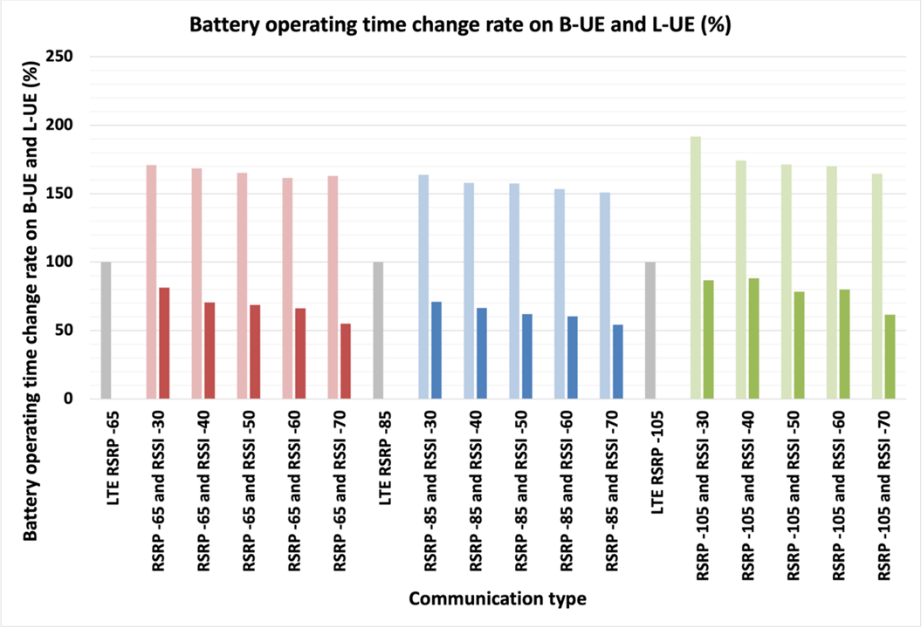

Figure 4-8 Percentage change in battery life by implementing energy borrowing scheme in B-UE and L-UE

The light blue bars show the rate of change of B-UE at RSSI -30, -40, -50, -60, and -70 when the RSRP is -85, and the blue bars show the rate of change of L-UE under the same conditions. By applying the energy borrowing method, the B-UEs showed the following results in this experimental environment. It was found that the average drive time could be extended by 155%. On the other hand, the L-UE was found to be able to extend its battery life to 70% of its normal use by sharing its own battery resources with other terminals.

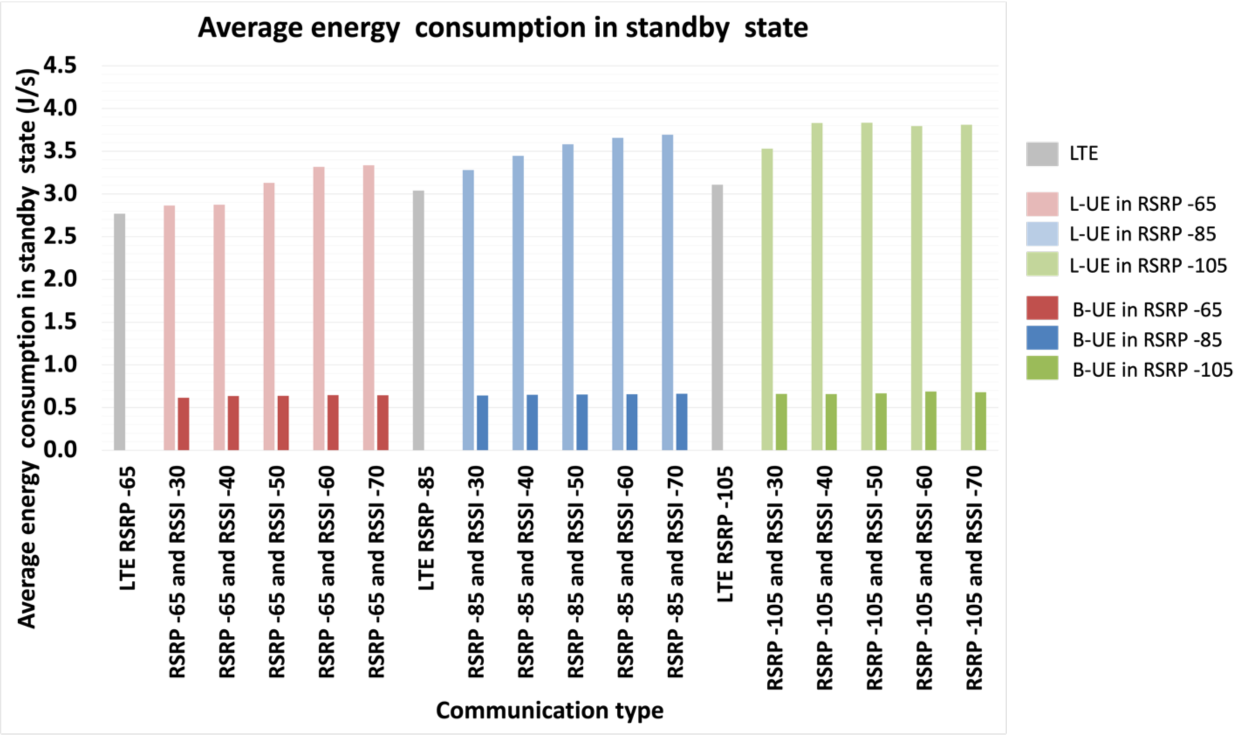

Figure 4-9 Standby power consumption in B-UE and L-UE

In addition, standby power consumption was also measured. Figure 4-9 shows power consumption in standby mode. The gray bars indicate the standby power consumption for LTE-only without D2D, and the RSRPs from left to right are -65, -85, and -105 dBm. And the pink bar graph shows the power consumption of L-UE at the respective D2D strength when the RSRP of L-UE is -65 dBm. The red s-bar graph shows the power consumption of the B-UE under the same conditions. The light blue bar graph shows the power consumption of L-UE at each RSSI when the RSRP of L-UE is -85 dBm, and the blue bar graph shows the power consumption of B-UE. And the light green bar chart shows the L-UE for each RSSI when the RSRP of the L-UE is -105 dBm, and the dark green bar chart shows the power of the B-UE. As can be seen from this, the power consumption of the L-UE as the lender is higher than that of LTE, but the power consumption of the B-UE as the borrower is greatly reduced. It can also be seen that the B-UE consumes significantly less power than LTE and L-UE, confirming that D2D can be used to reduce standby power consumption.

4.4 Simulation study

4.4.1Overview of the Simulation

Based on the measurement results described in 4.3.2, simulations were performed. The simulation reproduces the actual environment and clarifies how much the battery life of the B-UE can be extended by using the proposed method. In addition, by setting an upper limit for the L-UE's power lending, the relationship between the power burden on the L-UE and the extension of the B-UE's battery life will be analyzed. Furthermore, by setting an upper limit to the amount of power lent to the L-UE, the proposed scheme aims to prevent a particular terminal from significantly lending power and draining its battery. Therefore, the fairness of the scheme by setting an upper limit is verified using the fairness index.

4.4.2Simulation Parameters and Scenario

The simulation scenario is as follows:

1. The environment to be reproduced in the simulation is one train car. The train was chosen as the scene where smartphones are used on a daily basis. As a result of a survey of 500 men and women who commute by train, 93.8% of them answered that they use smartphones [45], so we set this as the environment in which the simulation would be reproduced as a scene in which they use smartphones on a daily basis. The number of passengers is assumed to be 77, with a 50% occupancy rate, and each passenger is assumed to have one smartphone, so that there are 77 smartphones in one train car. The vehicles are assumed to be those in [46].

2. B-UEs are assumed to be 10% of the total number of B-UEs, and the remaining battery power of B-UEs is assumed to be 10%. The L-UE candidates shall be 30, 50, and 90% of the total number of L-UEs, and the remaining battery capacity shall be 100%. On average, the B-UE downloads 100Mbytes of data once every 30 seconds. At that time, if an L-UE is found in the neighborhood, it communicates using the proposed method; if not, it communicates directly with the base station. Each time the B-UE communicates, it consumes power and the remaining battery power decreases.
3. Similarly, each time when the L-UE lends power, its remaining battery power decreases. In addition, the L-UE shall set an upper limit for the amount of power it lends, and if the upper limit is exceeded, it shall not participate in the scheme. The upper limit to be used this time is the total power lending limit, and if the limit is exceeded, no power will be lent.

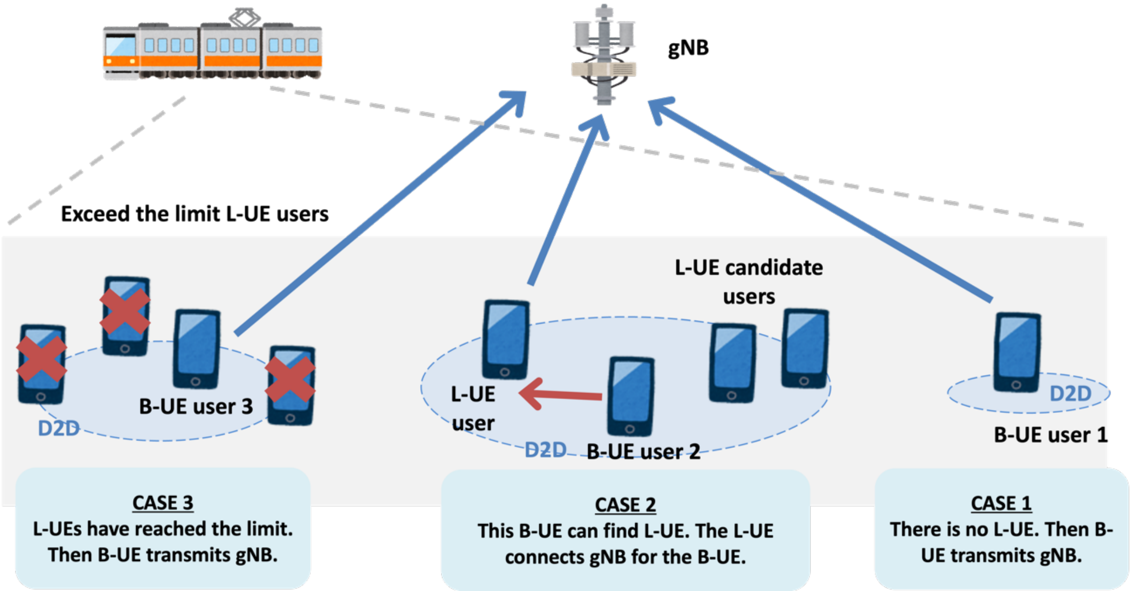

Figure 4-10 Simulation scenarios

Figure 4-10 summarizes the simulation scenarios and environment. In CASE 1, the B-UE searches for L-UE candidate terminals in the vicinity, but there are none, so the B-UE accesses the base station directly at its own station. The base station communicates with the user using the energy borrowing method because energy borrowing communication has been established. In CASE 3, the surrounding L-UEs have reached the energy borrowing limit and do not participate in the scheme, and the B-UEs communicate directly with the base station.

Therefore, the total power consumption of the B-UE is the sum of the power consumption when communicating is performed with the base station using the proposed method and the power consumption when communicating is performed with the base station at its own station because no L-UE is found.

Table 4-2 Simulation parameters

Parameters	Value
The number of users	77 users
B-UE ratio in all users	30, 50, 90%
L-UE ratio in all users	90%
The battery remaining in B-UE	10%
The battery remaining in L-UE	100%
LTE RSRP	-60, -74, -84, -96, -105, -115 dBm
D2D RSSI	-44, -52, -62, -74 dBm
The limit of the total lending energy	1,3,5,8,10,20,50,80,100%
The area of the simulation (The cabinet size of the train)	20×2.85m
The battery capacity	2800mAh
Average data birth interval	30 s
Data size	100 MB

The parameters of the simulation are shown in Table 4-2. As mentioned above, the number of users is assumed to be 77. One vehicle with 50% occupancy is reproduced. In addition, the percentage of B-UEs among them is 10% and the remaining battery capacity is 10%. The proportion of L-UEs is simulated at 30, 50, and 90% respectively; the remaining battery capacity of L-UEs is assumed to be 100%. The vehicle size is assumed to be 20 x 2.85 m. The parameters of the LTE RSRP and D2D RSSI are taken from the previous study [47]. In addition, the upper power lending limits shall be 1, 3, 5, 8, 10, 20, 50, 80, and 100%. These values are the percentage of the L-UE's own battery (%) that the L-UE is allowed to lend to the B-UE.

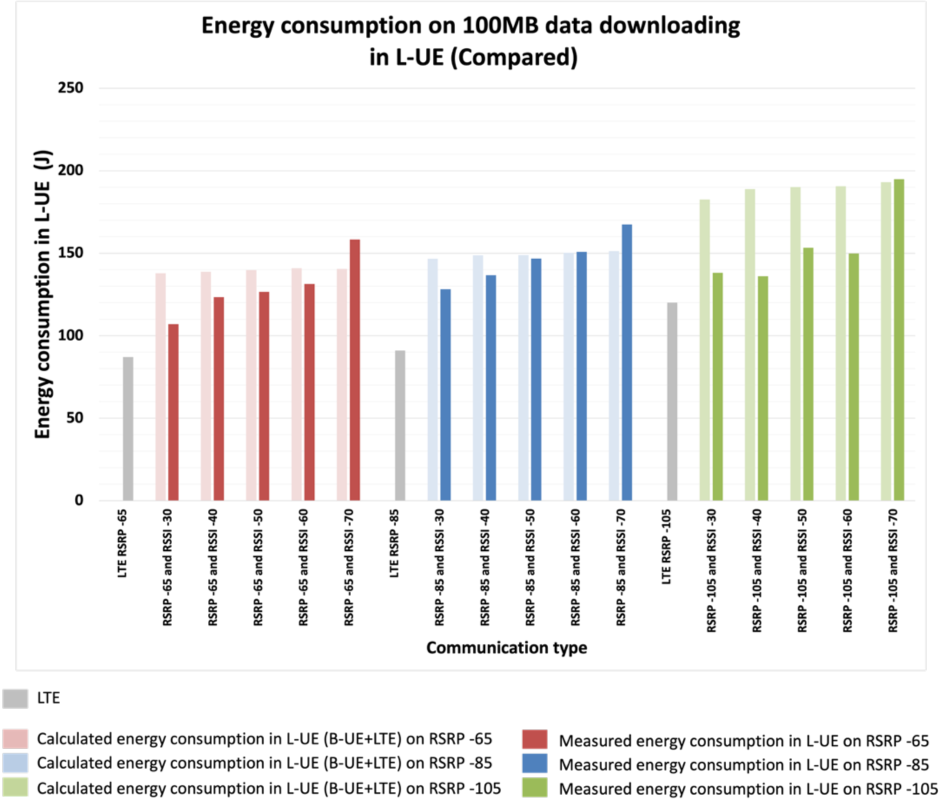

Figure 4-11 Calculated value obtained from measured power consumption of L-UE and power consumption of B-UE and LTE

The power generated by the L-UE when it lends power is the power generated by LTE plus the power generated by D2D. The gray bars in Figure 4-11 show the power consumption when acquiring 100 Mbytes at the own station at RSRP-65, -85, and -

105. The red, blue and dark green bars from left to right show the power consumption of the L-UE when 100 Mbytes are acquired by the B-UE shown in Section 4.3. And the pink, light blue and light green bar graphs shown next to these graphs are the combined power consumption of the B-UE and the power consumption at its own station. As can be seen in Figure 4-11 there is no significant difference and the same trend of power consumption increases as the RSSI becomes weaker, so the values described above were used in this simulation.

4.4.3Simulation Results

Simulation results are shown in Figure 4-12 which shows the relationship between the power lending limit and the extended battery life of B-UEs when 90% of all users are L-UEs. It is an indicator of how much battery life could be increased. The unit is minutes. This indicator is the difference between the battery time when communicating is performed with the base station without applying the method and the battery life time when the method is applied. It can be confirmed that in an environment where the power lending limit is low, such as 1%, the surrounding L-UEs quickly reach the limit and there are no terminals that can participate as L-UEs, and as a result, the B-UEs communicate with the base station at their own station and the battery life of the B-UEs does not increase much. In the present environment, the battery life of the B-UE increased significantly in the range of 3 to 8% of the upper limit of the power credit and did not change significantly when the upper limit was increased further. The extended battery life was 12.6 minutes. When the upper limit of power lending was set to 100%, i.e., L-UE lends power until it reaches 0%, the extended battery operation time was 13.9 minutes, showing no significant change depending on the upper limit. On the other hand, when the LTE reception strength was at its weakest (RSRP-115dBm), the extended battery run time was 17.4 minutes when the upper power lending limit was 1%. When the power lending upper limit was 100%, the impact was 33 minutes, compared to -60 dBm. Experiments have shown that the weaker the RSRP, the more power is consumed when communicating with the base station. Therefore, in an environment with a weak RSRP, the L-UE consumes a relatively large amount of power and reaches the upper limit relatively quickly. This is then considered to be the result because there are no more terminals from which the B-UE can borrow and it starts communicating with its own station.

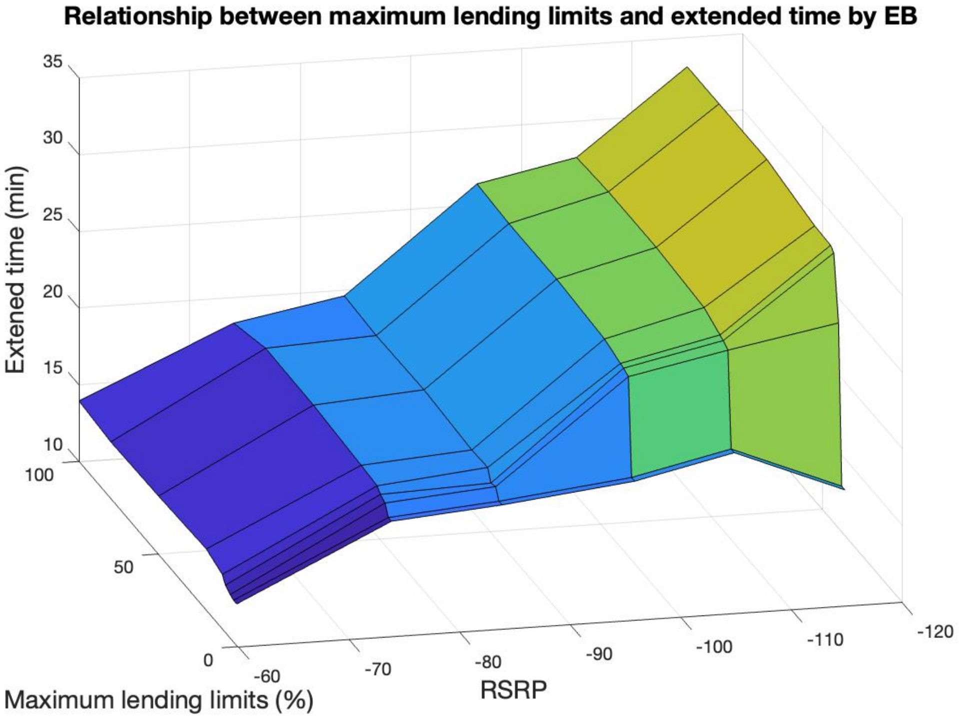

Figure 4-12 Relationship between power credit limit and extended battery run time (L-UE 90%)

Figure 4-13 also shows the relationship between the power lending limit and the extended battery life in B-UE when 30% and 50% of the total users are L-UEs and L-UEs, respectively. The lower graph shows the extended battery life when 30% of all users are L-UE, and the overlapping graph shows the extended battery life when 50% of all users are L-UE. It can be confirmed that the change in extended battery life when the user was a UE having a similar trend. The trend was found to be the same when L-UE was 90% as shown in Figure 4-12. On the other hand, a major difference when the L-UE is 90%, is that when the upper limit of the power loan is set low, the extended battery life is shorter than when the L-UE is 30% or 50%. For example, when L-UE is set at 90% and the maximum power credit limit is 1%, the battery life can be extended by 12 minutes at most. On the other hand, at 30%, the maximum battery life is 1.6 minutes, which is very short. Therefore, when there are few L-UEs in the vicinity and the upper limit of power lending is set to a small value, such as 1%, it was confirmed that this method has little effect on extending the battery life of B-UEs. On the other hand, in an environment with as many as 90% L-UEs, even when the upper limit is small (1-3%), the battery can be extended to a minimum of 12 minutes and a maximum of 20 minutes, indicating that the upper lending limit is closely related to the number of surrounding L-UEs.

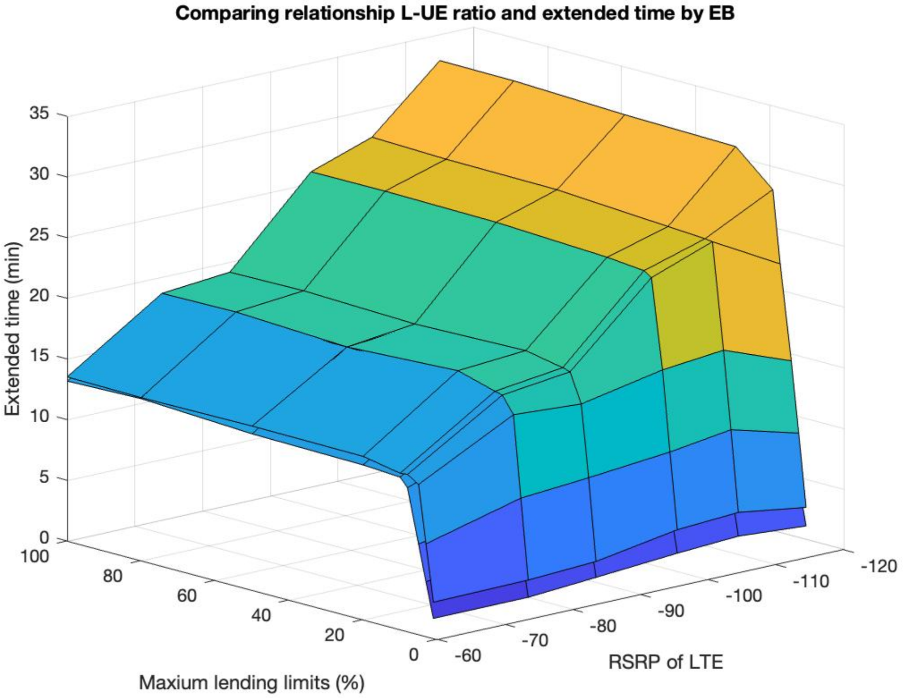

Figure 4-13 Relationship between power credit limit and extended battery run time (L-UE 30, 50%)

When the graphs are compared with the three conditions of 30, 50, and 90% L-UEs, the graphs are overlaid with 30, 50, and 90% from the bottom. This indicates that the higher the number of L-UE users, the longer the battery life can be extended. For any number of L-UE terminals, it was found that the battery life extension time is longer when the upper limit of power lending for each L-UE terminal is larger, and conversely, the battery life extension time is shorter when the upper limit of power lending for each L-UE terminal is smaller. The upper power lending limit at which the B-UE extension time was 10 minutes or longer for all RSRPs in this simulation, was 1% for the 90th percentile (minimum 12 minutes and maximum 20 minutes in that case), 5% for the 50th percentile (minimum 12 minutes and maximum 17 minutes), and 8% for the 30th percentile (minimum 11 minutes and maximum 16 minutes).

Next, we examined the relationship between the upper limit of power lending for this method and the fairness of the method. Figure 4-14 shows the relationship between the power lending upper limit and Jain's fairness index (FI) [48] when the L-UE is 90% of all users. A situation in which a particular L-UE is lending power to an extreme degree is considered to be less fair, while a situation in which the entire surrounding L-UE terminals are sharing and lending power is considered to be more fair. In this study, fairness was verified using Jain's fairness index (FI) as a measure of fairness, which can be expressed as 0.0 to 1.0, with a value close to 1.0 indicating fairness.

We checked how much the FI changes when there is no upper limit for power lending and all the remaining battery capacity of the L-UE is lent, and when the method is introduced with an upper limit for power lending, which is "up to what percentage of each L-UE terminal can be lent. As shown in Figure 4-14, when the upper limit is as low as 1%, B-UEs borrow from other terminals one after another, resulting in a situation where 1% is lent to each L-UE as a whole, and FI becomes very high. This trend is similar up to 5%. However, it can be seen that the FI is getting lower as the upper limit is raised above that level. This indicates that certain L-UE terminals are lending more power. Since the proposed scheme aims at extending the battery life of the B-UE, the B-UE selects the terminal with the strongest RSSI value as the L-UE. Therefore, it can be said that this happens because the B-UE preferentially selects the terminal with the lowest power consumption. Based on this result, it can be confirmed that by setting an upper limit for power lending to the L-UE, it is possible to prevent a situation in which only certain L-UE terminals lend power, and to create a situation in which multiple terminals in the surrounding area gradually lend power to each other. Also, by setting the upper limit in this way, it can be said that excessive battery drain of the L-UE can also be prevented.

The results of Figures 4-12 and 4-13 together with the results of this simulation evaluation indicate that setting the upper limit of power lending to 5-8% will ensure sufficient battery life extension time while maintaining FI.

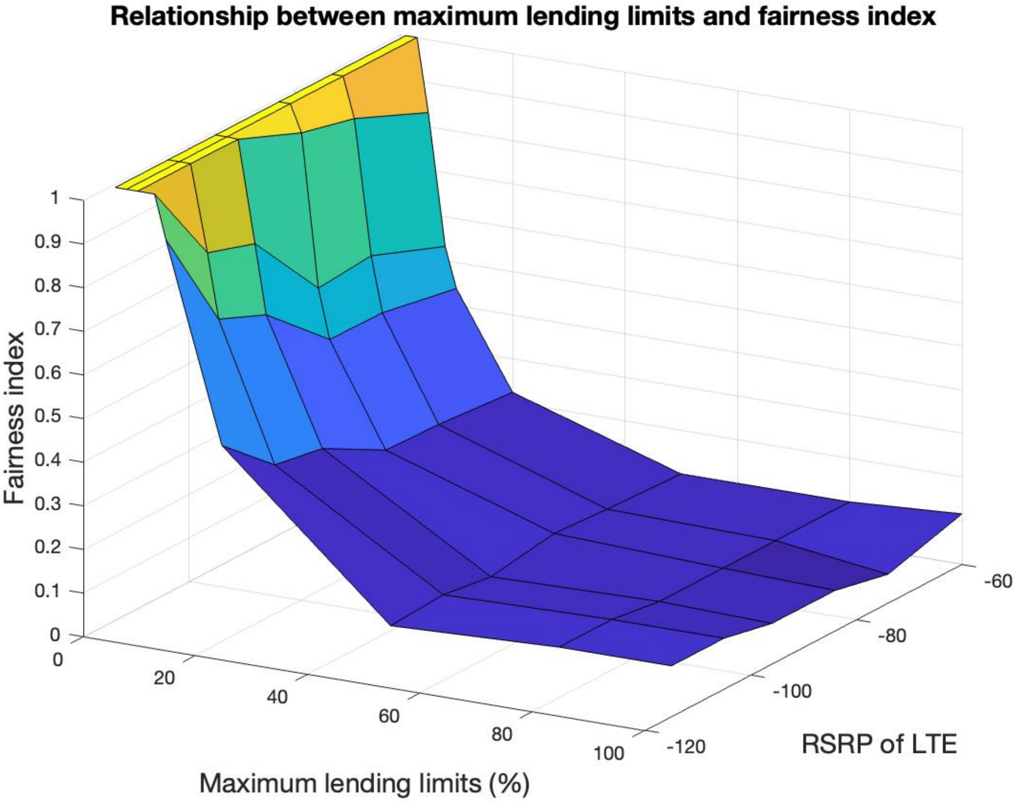

Figure 4-14 Relationship between power credit limit and FI (90% L-UE)

Figure 4-15 also shows the FI when L-UE is 30, 50, and 90% of all users. The reason for the lowest FI at 90% and the highest FI at 30% can be attributed to the following reasons: When L-UE is 30%, the number of L-UE terminals is relatively small, so the percentage of terminals that are leased up to the upper limit is high as a percentage of the total number of L-UE terminals. Thus, the FI will be higher because L-UE terminals will lend power at the same level overall. On the other hand, in a situation where the number of L-UEs is as high as 90%, the percentage of terminals that lend power up to the upper limit is lower relative to the population of L-UEs. Therefore, the FI will be low. Therefore, when considering fairness, it may be possible to make the scheme more fair by making the power lending upper limit variable within the range of user settings to some extent depending on the number of surrounding L-UEs. It is also conceivable that FI may vary depending on the number of surrounding L-UE terminals and their power lending upper limit settings, depending on the situation. It is then conceivable that by running the method in all such environments, the FI will level out. In order to guarantee optimal FI while ensuring extended battery operation time, it is necessary to consider a method that acquires L-UE density information, terminal information, etc. before executing the method, and executing energy borrowing communication based on FI and extended time prediction.

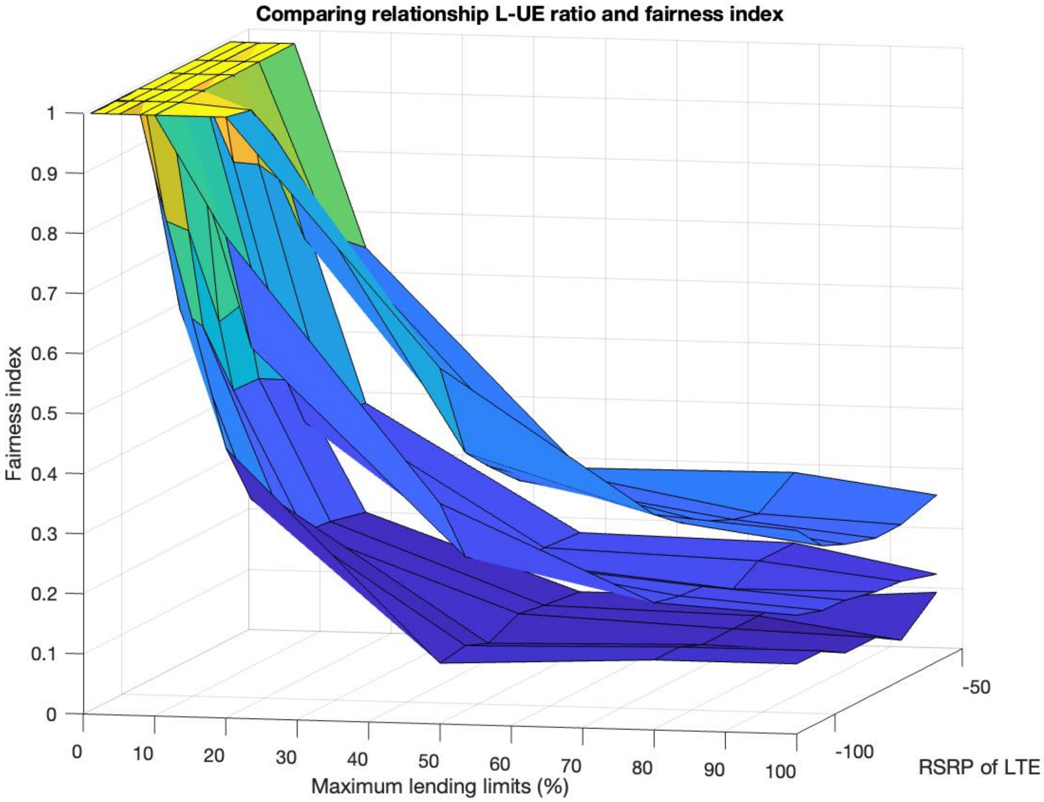

Figure 4-15 Relationship between power credit limit and FI (30, 50% L-UE)

4.5 Summary

In this study, we proposed "energy borrowing transmission" in 5G. In addition, newly we examined a method that takes into account the power burden on L-UE and fairness with surrounding terminals.

In the measurement experiments, we divided the power consumption during communication into three categories: power borrowing, power lending, and direct communication with base stations, and analyzed power consumption and battery depletion when communicating with base stations, and power consumption and battery depletion when using the proposed method for both the borrowing and lending sides. In the simulation, we reproduced the environment inside a train and introduced an upper limit for power lending to verify the impact of the upper limit on fairness and the relationship with the effect of extending the battery life of the B-UE. From the results of the experiments and simulations, it is confirmed that the use of the power lending upper limit for L-UEs prevents the concentration of power lending to specific L-UEs and maintains fairness. The upper limit also prevents excessive battery drain on L-UEs. In the future, it is necessary to consider extending the method to ensure the effect of extending battery life while guaranteeing FI, for example by making the upper limit value variable based on the surrounding terminal density and the ratio of B-UEs and L-UEs. It is necessary to examine the method and verify its effectiveness, and at the same time, update the method for beyond 5G.

Chapter 5
Conclusions and Future Works

In this thesis, we proposed an energy-borrowing transmission scheme based on D2D communication. Accordingly, we defined and proposed a novel concept of using D2D to virtually borrow power from other terminals via communication, and designed a system based on this concept. Using this method, we addressed the problem of battery life, which is one of the most common complaints of several users. In addition, we studied the basic scheme and confirmed the effectiveness of the proposed method by measuring its power consumption. In addition, we considered the power lender and extended the proposed system to consider the burden on the power lender and the fairness of the system.

Chapter 1 introduced this study. First, a description of the current state of mobile services was provided. Then, the problems and issues addressed in this study were presented. The results of a questionnaire survey on battery life, which has been a complaint of users for some time, were also presented. Subsequently, an overview of D2D communication was provided, and the positioning of this research was discussed. Finally, the structure of this paper and the outline of each chapter were also presented.

Chapter 2 introduced the basic technology of D2D communication, which is the focus of this study. The basic ideas were explained and typical communication models of D2D communication were described, including previous research on D2D communication combining cellular communication and Wi-Fi Direct, which forms the basis for the proposed method of this study. The concepts and protocols were also described.

In Chapter 3, we proposed the basic concept of the proposed "Energy Borrowing Transmission Scheme" using D2D communication and designed a communication scheme that virtually borrows battery resources from neighboring terminals using D2D communication with Wi-Fi Direct. Experiments and simulations were conducted to verify the effectiveness of the proposed scheme. Experiments were conducted using smartphones to measure the actual power consumption when downloading data. Experiments were conducted in an anechoic chamber to reproduce multiple reception environments, as well as in multiple outdoor environments, to verify the effectiveness of the proposed method in common scenarios. The results demonstrated that D2D communication using Wi-Fi consumes less power and is expected to have a longer battery life. Using these results, we also confirmed that the proposed method is effective in extending the battery life by using the proposed method in a simulation that reproduced the environment inside a train.

In Chapter 4, we propose a method to set an upper limit on the amount of energy that can be lent out, based on the scheme proposed in Chapter 3. This would allow the consideration of the electric power burden on the lender. In addition, it ensures fairness among lender terminals. There are two types of power to be lent: the first is a daily limit on the amount of power that can be lent and the second is a limit on the amount of power that can be lent for the pair that is currently lending power. This capped amount ensures fairness by lending power in small increments at surrounding terminals rather than having only one terminal lending an excessive amount of power. The effectiveness of the proposed method was verified via experiments and simulations. In the experiment, in addition to the cellular communication and power borrower, the power lender was also subjected to the measurement of power consumption. Based on the experimental results, a simulation was conducted to reproduce the actual train environment. We investigated the effect of setting an upper limit on the amount of power to be lent on extending the battery life of the borrower and the fairness of the lender.

The verification results indicated that setting an upper limit ensures fairness. We also verified the relationship between the battery running time and fairness of energy lending for L-UEs by setting the upper limit.

In this study, we proposed a scheme for communicating using D2D communication while virtually borrowing battery resources from neighboring terminals. We also improved the scheme by setting an upper limit on the amount of power to be lent, considering the burden on the terminal and fairness.

However, we believe that the proposed method can be improved further. To further improve the effectiveness of the method, we present the following ideas for future research:

- Appropriate communication schemes based on mobility and user usage (communication trends). By considering mobility and human communication behavior, it is expected that the battery life can be extended more effectively.
- Density of UEs in the entire area. It is necessary to consider extending the method, to ensure the effect of extending the operation time while guaranteeing FI, for example, by dynamically altering the upper limit variable according to the surrounding terminal density, the ratio of B-UEs to L-UEs, and other environmental factors.
- Further applications of D2D communication technology include the consideration of multi-hop and single-hop. Lending power via coordination among multiple terminals.
- Optimization of economic incentives to encourage energy lending. Concepts for points or coupons.
- Finally, the scheme should be improved to make it compatible with B5G.

Bibliography

[1] ITU, “M.2083: IMT Vision - "Framework and overall objectives of the future development of IMT for 2020 and beyond”, Recommendation M.2083, Sep. 2015

[2] ITU, “Report ITU-R M.2370-0 IMT traffic estimates for the years 2020 to 2030”, Jul. 2015

[3] Ministry of Internal Affairs and Communications, “Information and Communications White Paper 2020, Part 1, Section 2: Beyond 5G”, 2021

[4] Media Marketing Data labo,”Survey on smartphone satisfaction and dissatisfaction”, 2015, Accessed: Jun. 28, [Online] Available: https://mmdlabo.jp/investigation/detail_1499.html

[5] Mobile Market, "Smartphone Fatigue Survey Questionnaire.", 2021, Accessed: Jun. 28. [Online]. Available: https://keitaiichiba.co.jp/news/?p=2696

[6] Arash Asadi, Qing Wang, Vincenzo Mancuso, “A Survey on Device-to-Device Communication in Cellular Networks”, IEEE Communications Surveys & Tutorials, Volume: 16, Issue: 4, Fourth quarter 2014

[7] Pradip Kumar Barik, Chetna Singhal, Raja Datta, “Throughput enhancement using D2D based relay-assisted communication in cellular networks,” 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Montreal, QC, 2017

[8] H. Zhang, Y. Liao, and L. Song, "D2D-U: Device-to-Device Communications in Unlicensed Bands for 5G System," in IEEE Transactions on Wireless Communications, vol. 16, no. 6, pp. 3507-3519, June 2017.

[9] Guopeng Zhang, Kun Yang, Peng Liu, Junyi Wei, “Power Allocation for Full-Duplex Relaying-Based D2D Communication Underlaying Cellular Networks”, IEEE Transactions on Vehicular Technology, Volume: 64, Issue: 10, Oct. 2015

[10] Siddharth Sharma, Naveen Gupta, Vivek Ashok Bohara, “OFDMA-Based Device-to-Device Communication Frameworks: Testbed Deployment and Measurement Results”, IEEE Access, Volume: 6, PP:12019 – 12030, Mar. 2018

[11]S. Mumtaz, K. M. S. Huq, A. Radwan, J. Rodriguez, and R. L. Aguiar, "Energy efficient interference-aware resource allocation in LTE-D2D communication," 2014 IEEE International Conference on Communications (ICC), Sydney, NSW, 2014, pp. 282-287.

[12]Sa Xiao, Xiangwei Zhou, Daquan Feng, Yi Yuan-Wu, Geoffrey Ye Li, Wei Guo, "Energy-Efficient Mobile Association in Heterogeneous Networks with Device-to-Device Communications," in IEEE Transactions on Wireless Communications, vol. 15, no. 8, pp. 5260-5271, Aug. 2016

[13]3GPP TR36.843 V1.2.0, “Study on LTE device to device proximity services; Radio aspects”, 2014

[14]3GPP RR 22.803 V12.2.0 “Feasibility study for Proximity Services (ProSe)”, 2013.

[15]Hiroki Nishiyama, Masaya Ito, and Nei Kato, “Relay-by-Smartphone: Realizing Multihop Device-to-Device Communications,” IEEE Communications, vol. 52, no. 4, pp. 56-65, Apr. 2014.

[16]Tohn Furutani, Yuichi Kawamoto, Hiroki Nishiyama, Nei Kato, “A novel information diffusing method with virtual cells based Wi-Fi direct in disaster area networks” 2018 IEEE Wireless Communications and Networking Conference (WCNC), Apr. 2018

[17]Mohsen Nader Tehrani, Murat Uysal, Halim Yanikomeroglu, “Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions”, IEEE Communications Magazine, Volume: 52, Issue: 5, May. 2014S Mobile Computing, Volume: 16, Issue: 8, Aug. 2017

[18]Arash Asadi, Vincenzo Mancuso, “WiFi Direct and LTE D2D in action”, 2013 IFIP Wireless Days (WD), Nov. 2013

[19]Arash Asadi, Vincenzo Mancuso, “Network-Assisted Outband D2D-Clustering in 5G Cellular Networks: Theory and Practice”, IEEE Transactions on Mobile Computing, Volume: 16, Issue: 8, Aug. 2017

[20]C. Yao, H. Zhang, and L. Song. “WiFi Multihop: Implementing Device-to-Device Local Area Networks by Android Smartphones”, 16th ACM International

Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc '15), June 2015

[21]Longhao Zou, Ali Javed, Gabriel-Miro Muntean, "Smart mobile device power consumption measurement for video streaming in wireless environments: WiFi vs. LTE", 2017 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), June. 2017

[22]Sneha Tipugade, Chetna Singhal, "Adaptive Multimedia Streaming between Heterogeneous Users using D2D and Dynamic Wi-Fi Configuration", 2018 International Conference on Computing, Networking and Communications (ICNC), Mar. 2018S

[23]Yaodong Zhang, Chunxiao Jiang, Zhu Han, Shui Yu, Jian Yuan, "Interference-Aware Coordinated Power Allocation in Autonomous Wi-Fi Environment", IEEE Access Volume: 4, pp: 3489 – 3500, June. 2016.

[24]Bushra Ismaiel, Mehran Abolhasan, Wei Ni, David Smith, Daniel Franklin, Eryk Dutkiewicz, Marwan M. Krunz, Abbas Jamalipour, "PCF-Based LTE Wi-Fi Aggregation for Coordinating and Offloading the Cellular Traffic to D2D Network", IEEE Transactions on Vehicular Technology, Volume: 67, Issue: 12, Dec. 2018

[25]Eftychia Datsika, Angelos Antonopoulos, Nizar Zorba, Christos Verikoukis, "Green Cooperative Device–to–Device Communication: a Social–Aware Perspective", IEEE Access, Volume 4, pp: 3697 – 3707, June 2016

[26]Sihan Liu, Yucheng Wu, Liang Li, Xiaocui Liu, Weiyang Xu, "A Two-Stage Energy-Efficient Approach for Joint Power Control and Channel Allocation in D2D Communication", IEEE Access, Volume: 7, pp: 16940 – 16951, Jan. 2019

[27]Bidi Ying, Amiya Nayak, "A Power-Efficient and Social-Aware Relay Selection Method for Multi-Hop D2D Communications", IEEE Communications Letters, Volume: 22, Issue: 7, pp: 1450 – 1453, Jul. 2018

[28]Samsung, Samsung Galaxy S10, Accessed: Jun. 28. [Online]. Available: https://www.galaxymobile.jp/galaxy-s10/specs/

[29]The Institute of Electronics, Information and Communication Engineers "Group 4 (mobile and wireless) - Part 5 (mobile IP, ad hoc networks) Chapter 2: Ad Hoc

Networks, Knowledge base" Accessed: Jun. 28. [Online]. Available: http://ieice-hbkb.org/files/04/04gun_05hen_02.pdf

[30]Akikatsu Kosuga, Satoko Itaya, Peter Davis, and Hidekazu Umeda, "A New World Opened by Ad Hoc Networks (Part 1)", IPSJ Magazine Vol.44 No.10, Oct 2003

[31]Jinchuan Tang, Gaojie Chen, Justin P. Coon, "Joint Coverage Enhancement by Power Allocation in Poisson Clustered Out-of-Band D2D Networks", IEEE Transactions on Vehicular Technology, Volume: 67, Issue: 12, Dec. 2018

[32]Yue Qiu, Yinghe Wang, Chong Tan, Min Zheng, Kai Yu, "Joint resource allocation algorithm based on throughput maximization in D2D communication", 2015 4th International Conference on Computer Science and Network Technology (ICCSNT), December 2015

[33]Yaodong Zhang, Chunxiao Jiang, Zhu Han, Shui Yu, Jian Yuan, "Interference-Aware Coordinated Power Allocation in Autonomous Wi-Fi Environment", IEEE Access Volume: 4, pp: 3489 – 3500, June. 2016.

[34]F. Bouhafs, M. Seyedebrahimi, A. Raschellà, M. Mackay, Q. Shi, "Per-Flow Radio Resource Management to Mitigate Interference in Dense IEEE 802.11 Wireless LANs", IEEE Transactions on Mobile Computing, Volume: 19, Issue: 5, pp:1170 – 1183, May. 2020

[35]Virginie Deniau, Christophe Gransart, Grecia L. Romero, Eric Pierre Simon, Joumana Farah, "IEEE 802.11n Communications in the Presence of Frequency-Sweeping Interference Signals", IEEE Transactions on Electromagnetic Compatibility, Volume: 59, Issue: 5, pp: 1625 – 1633, Oct. 2017

[36]Mohammed Hirzallah, Wessam Afifi, Marwan Krunz, "Full-Duplex-Based Rate/Mode Adaptation Strategies for Wi-Fi/LTE-U Coexistence: A POMDP Approach", IEEE Journal on Selected Areas in Communications, Volume: 35, Issue: 1, pp: 20 – 29, Jan. 2017

[37]IEEE 802.11ax: The Sixth Generation of Wi-Fi White Paper, [Online] Available: https://www.cisco.com/c/en/us/products/collateral/wireless/white-paper-c11-740788.html

[38]3GPP TS 38.304 V15.1.0 “NR; User Equipment (UE) procedures in idle mode and in RRC Inactive state”, 2018

[39]Mingjun Wang; Zheng Yan, “Security in D2D Communications: A Review”, 2015 IEEE Trustcom/BigDataSE/ISPA, Aug. 2015

[40]Jin Cao; Maode Ma; Hui Li; Ruhui Ma; Yunqing Sun; Pu Yu; Lihui Xiong, “A Survey on Security Aspects for 3GPP 5G Networks”, IEEE Communications Surveys & Tutorials (Volume: 22, Issue: 1, Firstquarter 2020), November 2019

[41]3GPP TS 23.502 V15.5.1 “Procedures for the 5G System (5GS)”,2019

[42]3GPP TS 23.501 V15.1.0 “System architecture for the 5G System (5GS)”,2018

[43]Samsung, Samsung Galaxy S5 ACTIVE SC-02G, Accessed: Jun. 28. [Online]. Available: https://www.nttdocomo.co.jp/support/product/sc02g/spec.html

[44]TRYGLE, TEYGLE POWER BENCH, Available: https://trygle.com/

[45]Bizhits Corporation, "Attitude Survey on Smartphone Use During Train Commuting," 2021, Accessed: Jun. 28. [Online]. Available: https://bizhits.co.jp/media/archives/10396

[46]Tokyo Metro, Vehicle Serise 10000 of Yurakucho Line and Fukutoshin Line, , Accessed: Jun. 28. [Online] Available: https://www.tokyometro.jp/corporate/enterprise/passenger_rail/cars/working/yur-fuk_10000/index.html

[47]Megumi Saito, Takashi Koshimizu, Zhenni Pan, Jiang Liu, Hayato Nakazawa, and Shigeru Shimamoto,"Energy Borrowing Transmission Scheme Based on D2D Communication for 5G Networks", IEEE Access (Volume: 9 Page(s): 165841 - 165853), December 2021

[48]D.-M. Chiu and R. Jain, “Analysis of the increase and decrease algorithms for congestion avoidance in computer networks”, Computer Networks and ISDN Systems, vol. 17, pp. 1-14, 1989.

Research Achievements

Journal Article

- 齋藤恵, 仲沢隼斗, パン・ジェニー, 劉江, 嶋本薫 , "D2D 通信を用いた電力貸借通信における電力負担を考慮した端末選択手法の研究" 日本シミュレーション学会和文論文誌 14 巻 1 号, June 2022.
- Megumi Saito, Takashi Koshimizu, Zhenni Pan, Jiang Liu, Hayato Nakazawa, and Shigeru Shimamoto,"Energy Borrowing Transmission Scheme Based on D2D Communication for 5G Networks", IEEE Access (Volume: 9 Page(s): 165841 - 165853), December 2021
- T. Hu, Z. Pan, M. Saito, J. Liu, S. Shimamoto, "A Triple-Band Antenna Loaded with Reflector Surface for WLAN and 5G", Journal of Communications, vol. 15, no. 10, pp.729-734, Dec. 2021
- Hossain; Z. Pan; M. Saito; J. Liu; S. Shimamoto, "Robotic Inner Signal Propagation and Random Access over Hybrid Access Scheme", International Journal of Computer Networks and Communications, vol. 12, no. 4, pp. 71-89, July, 2020
- Dhakal Dhruba Raj, Zhenni Pan, Megumi Saito, and Shigeru Shimamoto. "Dynamic Resource Allocation in Non-orthogonal Multiple Access Using Weighted Maximin Fairness Strategy for a UAV Network." Journal of Signal Processing Systems 92, no. 12 (2020): 1397-1406.
- Abir Hossain, Zhenni Pan, Megumi Saito, Jiang Liu, Shigeru Shimamoto, "Multiband Massive Channel Random Access in Ultra-Reliable Low-Latency Communication", IEEE Access, Volume: 8, pp. 8149281505, April 2020
- Zhenni Pan, Megumi Saito, Jiang Liu, and Shigeru Shimamoto, "P -Persistent Energy-Aware Handover Decisions Employing RF Fingerprint for Adaptive-Sized Heterogeneous Cellular Networks", IEEE Access, Volume 7, Pages: 52929-52944, Apr. 2019

- Z. Pan, M. Saito, J. Liu, and S. Shimamoto, “Topology-aware Self-Energy, Configuration Employing Neuron Control for Two-tier Femtocell Networks”, Journal of Advanced Simulation in Science and Engineering 2018 Volume 10 Issue 2 Pages 59-68, 2018.03

International Conferences

- Genta Ishii, Megumi Saito, Zhenni Pan, Jiang Liu, Shigeru Shimamoto, “Wireless Power Transmission Scheme Employing Phase Control for WSN, 2021 18th IEEE Annual Consumer Communications and Networking Conference(CCNC), Las Vegas USA [Online],Jan.2021.
- Tengfei Hu, Zhenni Pan, Megumi Saito, Jiang Liu, Shigeru Shimamoto,”A Triple-Band Antenna Loaded with Reflector Surface for WLAN and 5G Applications”, International Conference on Computer and Communication Systems, Shanghai, China,2020.
- S. Gengtian, T. Koshimizu, M. Saito, P. Zhenni, L. Jiang and S. Shimamoto, “Power Control Based on Multi-Agent Deep Q Network for D2D Communication,” 2020 International Conference on Artificial Intelligence in Information and Communication (ICAIIC), pp. 257-261, doi: 10.1109/ICAIIC48513.2020.9065192, Fukuoka, Japan, Feb. 2020.
- Md.Abir Hossain, Megumi Saito, Zhenni Pan, Jiang Liu, and Shigeru Shimamoto, "Orthogonal Frequency Subcarrier-based Multiple Random Access in Ultra Reliability and Low Latency Communication", Workshop - Cyber-Physical Networking (CPN’20),IEEE CCNC 2020
- Megumi Saito, “D2D communication in 5G networks”, Northeast Asia Symposium on IoT with Intelligence 2019, Beijing university of posts and telecomunications, Beijing, China, Sep. 2019
- Kazutoshi Yoshii, Megumi Saitou, Jiang Liu, Shigeru Shimamoto, “Prediction of Ionospheric Fading for Long Distance Emergency Communication”, 2019 IEEE International Conference on Communications Workshops (ICC Workshops), 20-

24 May 201

- Tojoarisoa Rakotoaritina, Megumi Saito, Zhenni Pan, Jiang Liu and Shigeru Shimamoto, “Multilayered Metamaterial Low Profile Antenna for IoT Applications”, Japan Society for Simulation and Technology JSST2018, Sep. 2018
- Megumi Saito, Li Xiwen, Zhenni Pan, Liu Jiang, Shigeru Shimamoto, “Cooperative Access among UEs in Cellular Networks”, IEEE and ACM CTS 2015, Mobile Systems and Wireless Sensor Networks for Collaboration, p434-440, Jun, 2015
- Zhenni Pan, Megumi Saito, Jiang Liu, Shigeru Shimamoto, “Neuron Control-Based Power Adjustment Scheme for Sleep Two-tier Cellular Networks”, IEEE WCNC 2014, p.3201-3206, Apr. 2014

Workshops

- Megumi Saito, Zhenni Pan, Liu Jang and Shigeru Shimamoto, "Relaying Scheme for Low Energy Consumption Cellular Networks employing D2D communications", JWUHU Workshop 2018, Waseda University, Japan, Dec.2018
- Megumi Saito, Zhenni Pan, Liu Jiang, andShigeru Shimamoto, “Experimental study on Energy Saving Transmission Using D2D (Wi-Fi) and LTE”, Join Workshop between Korea, Japan and Malaysia, Hanyang Univ,Waseda Univ, UKM & UMS, 2017.12

Domestic conferences

- 吉井一駿, 松下惟晟, 齋藤恵, 嶋本薫, "5Gシステムによる4K解像度VR映像伝送実験", 電子情報通信学会 通信ソサイエティ大会 一般セッション B-15-102019
- 坂本 祐基, 功刀 紀樹,吉井 一駿, 齋藤 恵, ジェニー パン,嶋本 薫, 太田 現一郎, 徳田 清仁,佐藤 拓朗, 野崎 大地,岡本 航輝,持田 透, 山田 雅也, “28GHz帯における入射角別の反射,透過特性および,伝搬モデルに関する研究”, 電子情報通信学会技術研究報告 信学技報 117(456), 143-148, 2018年2月

- Megumi Kawabata, Megumi Saito, Shigeru Shimamoto,"A Study on Communication Scheme of Public Safety Network in Wide-Area Disaster Situation", 電子情報通信学会技術研究報告 信学技報 115(472), 79-84, 2016
- Zhenni Pan, Megumi Saito, Jiang Liu, Shigeru Shimamoto, "Energy-sensitive Handoff Scheme Employing RF Fingerprint For Cell Sizing Based Heterogeneous Cellular Networks", 電子情報通信学会技術研究報告 113(456), 145-150, RCS, 2014 年 3 月