Local Information Sharing System With Wireless Device-to-Device Communications

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ABSTRACT This study aims to develop a system of device-to-device (D2D) communications for information collection, distribution and sharing among local communities. It establishes a D2D testbed with low power consumption and solar power supply to evaluate the performance of the proposed system. Devices in the system can communicate with each other autonomously without a centralized control device when they are within a certain distance. A single device does not result in a dominant effect for the whole system, which ensures system robustness. To validate the performance of the designed system, a simulation is used to confirm the effectiveness of the system. Moreover, in cooperation with local communities, the system has been developed and deployed in some areas of Tokyo and Kyoto, Japan. The devices were deployed on buses and fixed places along the bus routes. The experimental results show that the proposed system can work with moderate delay latency. Specifically, the latency performance obtained in the field experiments meets the system design criterion quite well, which validates the feasibility and effectiveness of the proposed system. In summary, the proposed D2D local information sharing system can work independently from the cellular system and any other existing wireless network systems, which is expected to provide more proprietary and different wireless services. The paper also gives some ideas for further system improvement.

INDEX TERMS Device-to-device (D2D) communications, information sharing system, distributed system, Internet of Things (IoT).

I. INTRODUCTION
In recent years, wireless applications for local information sharing are becoming more important. These applications can collect, distribute, and share local information among local users or devices, which is very useful for local communities when it comes to obtaining local daily life information such as bus information. To implement this kind of application, it is necessary to build a robust, low-latency, flexible, low-cost wireless network that consumes little power.

To build a wireless network for the mentioned applications, traditional centralized systems, such as cellular systems or wireless local area networks, are usually considered. These centralized systems have several outstanding characteristics such as high throughput and low error rate. However, in the case of large scale natural disasters such as an earthquake or tsunami, the base stations may be destroyed and the wireless networks may fail. Therefore, this study aims to design a wireless local information sharing system that utilizes device-to-device (D2D) communications to implement a distributed communication network. The system with distributed D2D communications can sustain a resilient wireless network so that the system can keep working even if any single device malfunctions.

For the next generation of wireless communication standards, D2D communication is an important emerging topic. For example, in 3GPP standards, D2D communication is considered to be a method for enhancing the connectivity of the telecommunication network [1]. Besides the telecommunication networks that are costly to set up, the communication standards for short-distance links such as Bluetooth [2] and WiFi† [3], are also developing D2D communications based on their existing standards.

For D2D communications, it is already one of the most popular research topics in wireless communication areas with numerous applications [4]–[16]. In the literature published in the network area, there are also several studies discussing...

†For WiFi, the technique developed for D2D communication is called “WiFi Direct.”
the construction of networks via D2D communications [17]–[21]. For example, Doppler et al. [17] discussed how one can build networks in the LTE-advanced environment via D2D technology. Fodor et al. [18] presented their design ideas about realizing D2D-assisted networks. Ghosh et al. [19] proposed theoretical points on how one can implement D2D communications in building homogeneous networks. Zou et al. [20] addressed an important function, which is discovering devices in proximity, in order to realize D2D communications.

This paper proposes a local information sharing system that can collect, distribute, and share local information via D2D communications. Because the system utilizes distributed a D2D communication structure, it can maintain network functions even in cases where some devices malfunction, and it is robust in the case of natural disasters. The contributions of this paper are as follows:

- It proposes a structure of wireless local information sharing system that realizes a distributed wireless network with D2D communication. The proposed system is suitable for collecting, distributing, and sharing local information among mobile devices, and is robust in situations where some devices suddenly malfunction.
- It evaluates the capabilities of the proposed system. The proposed system was established on buses and bus routes in some areas of Tokyo and Kyoto in Japan in order to conduct field experiments in cooperation with local communities. The field experimental results show that, the proposed system performs well in practice. Besides, although the scenario with a huge number of devices was not evaluated by field experiment due to the budget limitation, it was investigated by simulations to validate the performance of the proposed system.
- In addition, the technical limitations of the proposed local information sharing system utilizing D2D communications were investigated and discussed. According to the technical limitations, some possible solution ideas for further improvement such as central processing unit (CPU) board and medium access control (MAC) superframe redesign are discussed and presented.
- Moreover, this system introduces a less power-consuming circuit design and a solar power supply in the developed D2D testbed, which can make power consumption more efficient and meet the requirements of green communication.

The rest of this paper is organized as follows. The design ideas of the proposed system are introduced in Sec. II. Some experiments and simulations are conducted to validate the design ideas of the proposed system in Sec. III. Finally, some concluding remarks are given in Sec. IV.

II. SYSTEM DESIGN

This paper proposes a system that conducts local information collection, distribution, and sharing via D2D communications among devices. The whole system can be divided into inner and outer network parts, as shown in Fig. 1. The devices in the inner network part can communicate with each other to build a local network by D2D communications and can connect to the Internet via a device that is selected as a “gateway device.” The outer network part provides services from external information servers, such as public services, weather forecasts, company homepages, etc. The devices can be for public or private use; their location can be fixed or they can be installed in mobile vehicles. Devices for public use are termed public terminals (PTs), and those for private use are termed user terminals (UTs).

A. DEVICE DISCOVERY PROCESS

For the inner network part, the devices connect to each other to form a network in a distributed manner. The D2D connection is established between two devices when the distance between them is below threshold. The discovery process of each peer device (PD) in the network to discover the neighbor PD is shown in Fig. 2. Note that the message exchanges of the D2D discovery process are mainly initialized by the higher layer, rather than the MAC layer, and are realized in the MAC layer. Details of the D2D device discovery process are as follows [22]:
• The higher layer of the PD initiator (i-PD) triggers the discovery procedure by issuing a `discovery_request` primitive to its MAC layer.
• On receiving the `discovery_request` primitive, the MAC layer of the i-PD broadcasts a discovery request frame in the assigned frequency channel.
• Other PDs that capture the discovery request frame are referred to as response PDs (r-PDs). The MAC layer of the r-PD issues a `discovery_request_indication` primitive to its higher layer to report the discovery of an i-PD (end of one-way discovery).
• On receiving the `discovery_request_indication` primitive, the next high layer of an r-PD may issue a `discovery_response` primitive to its MAC layer if it decides to accept the discovery request.
• The MAC layer of each r-PD that receives a `discovery_response` primitive from its next high layer sends a discovery response frame to the i-PD in a corresponding channel.
• On receiving the discovery response frame, the i-PD sends an immediate ACK frame to the r-PD and issues a `discovery_confirm` primitive to its next high layer (end of two-way discovery).

There are two types of discovery procedures. The procedure with steps (i)–(iii) is called “one-way discovery”, while the procedure with steps (i)–(vi) is called “two-way discovery” which includes the confirmation process. Note that an r-PD that sent a discovery response frame may not receive the immediate ACK frame due to bad channel conditions or congestions with other PDs. In such a case, the r-PD re-sends discovery response frame and steps (v) and (vi) are repeated.

B. DEVICE TYPES

In the application scenarios, there are four types of devices corresponding to different applications.

1) SENSOR TYPE DEVICE
Sensor type devices are used to collect environment information such as temperature or humidity. The device is powered by a solar power system and is usually located on the top of the vending machine in experimental deployment, as shown in Fig. 3(a).

2) SIGNAGE TYPE DEVICE
Signage type devices provide bus location information and public service information such as time, weather, emergency information, advertisements, local community events,
and news. Signage type devices consist of two versions: (a) the stationary version, usually installed in the lobby of a town hall, hotel, or shopping mall in experiments, and (b) the bus version, usually installed on a bus. In addition, the implementation examples of signage type devices are shown in Figs. 3(b) and 3(c) for the stationary and bus versions, respectively.

3) PORTABLE TYPE DEVICE
Portable type devices are handy devices used for sending and reading messages within the device group. Portable type devices are implemented into two kinds: tag version devices and tablet version devices. These two kinds of devices are shown in Figs. 3(d) and 3(e).

4) HIGH-POWER TYPE DEVICE
High-power type devices are base-station-style devices powered by a solar power system and located on the rooftop of a building. High-power type devices are used for broadcasting emergency and high priority information to all devices, which is performed in a distributed manner. All the information from the other types of devices is sent to the network gateway through high-power type devices. The reason why this kind of device is called “high-power” is because its transmission power is 250 mW, whereas that of the other types is 20 mW. Note that 250 and 20 mW are the values specified in the Association of Radio Industries and Businesses standards [23]. The implementation example and power supply are given in Figs. 3(f) and 3(g).

Note that among the four types of devices, only portable type device is UT and the other three types are PTs. In the proposed system, all devices use the same transceiver, which is shown in Fig. 4. The transceiver operates at 920 MHz with 400 kHz bandwidth using a commercial chip and is compact in size. Community buses play a central role in the field experiments. A bus and the devices surrounding it form an ad hoc network and exchange data and information. The receiver of each device can check the attached log file and only accepts new data and information. The bus keeps running from location to location, and ad hoc networks are formed at each location. In this way, the same data and information can be gradually updated and shared by the whole local community.

The source of data and information includes websites, sensors, and input from the local community. The content currently delivered through the system includes date and time, local weather, transportation status, news, local government announcements, event information, local library announcements, advertisements, sensor data, and emergency information. The frequency of data updating depends on the density of devices as well as the number of buses in operation. One can imagine that the diffusion of data and information would be faster and wider if there were more devices in more vehicles (such as taxis or cabs). Besides, the high-power type devices are also introduced in the proposed system to increase the coverage area.

A number of techniques have been developed to realize the system features described above, including synchronization based on global positioning system (GPS), self-organized control based on a predesigned frame, delay tolerance, channel access based on combined TDMA and CSMA, and group communication [24].

C. ROBUSTNESS OF WIRELESS LINKS
The basic assumption of the proposed system is that, the data and information to be shared are delay-tolerant. Because some vehicles are used as main components in the proposed system for collecting and sharing information, it can be foreseen that certain delays would occur because of the bus circulation period. Data and information can be distributed as long as some links among the devices and buses are available, which may vary from time to time. The reliability of the proposed system is guaranteed with a trade-off between varying connectivity and time delay. In contrast, providing real-time services is becoming as important as reliability when bus location becomes an essential requirement. To enable real-time communication in the proposed system, reliable networks connecting all high-power type devices need to be built. Moreover, location data from the GPS receiver of a running bus at any location of the routes of interest must be captured by at least one of the high-power type devices. To increase the reliability of high-power type device links, the following new versions have been implemented:

1) SECOND VERSION OF HIGH-POWER TYPE DEVICES
The high-power type device is developed to work on a solar power system. It is mounted on the roofs of buildings where power supply is usually impossible. The battery capacity of the solar power system is 640 watt-hour (Wh), and the power consumption of the 250 mW transceiver is about 15 W. The operation time when fully-charged is calculated as

\[
\frac{640 \text{ Wh}}{15 \text{ W}} \approx 42 \text{ hours.}
\]
expressed as mW. It is known that the propagation path-loss model can be modeled by increasing the transmission power from 20 to 250 transceivers of the signage devices in the buses were remod- type devices for capturing location data, all the 920 MHz ground. Antenna gain was 0 dBi, and the measured result was devices are both fixed at a height of 1.5 m above the line-of-sight (LOS) environment can be expected for the 250 mW transceiver.

As there are some small hills and valleys along the bus routes of interest in Seika Town, additional high-power type devices are needed to overcome the shadowing or radio disconnection caused by the terrain or other objects. The proposed system was deployed along the bus routes in an area of 6.5 km × 8.0 km, as will be shown shortly.

D. MAC LAYER SUPERFRAME STRUCTURE DESIGN

The MAC layer superframe structure of the proposed system is shown in Fig. 6. Here, the time period of each slot for device data transmission is fixed, and the total MAC superframe length is 60 sec. According to the slot time period, there are three superframe patterns in the system: pattern-I, pattern-II, and pattern-III. The pattern-I frame has a 4 sec time period for each slot and can accommodate the superframe structure, as shown in Fig. 6(a). The pattern-II superframe has a 5 sec time period for each slot and can also accommodate the superframe structure, as shown in Fig. 6(b). Finally, the pattern-III frame has a 6 sec time period for each slot and can accommodate the superframe structure, as shown in Fig. 6(c).

Because devices can form a network in a distributed way, the network can work robustly even if some devices malfunction. This feature is very useful when huge natural disasters strike, such as earthquakes, typhoons, or tsunamis, when several devices are destroyed. The following sections present the simulations and field experiments conducted to evaluate the effectiveness and feasibility of the proposed system.

E. APPLICATION SCENARIOS

In this system, there are some application scenarios that are realized using the devices introduced in Sec. II-B.

1) ENVIRONMENTAL INFORMATION SHARING SERVICE

The sensor type devices can be used to collect environment information that can be relayed and shared with all the other devices by high-power type devices with almost real-time latency. This application is useful for local residents because the environment information can be collected by local sensors and broadcast to them with almost real-time transmission instead of receiving long-term information from a public service server that is far from the local area. This service can provide more accurate and instant local environment information than the information provided by the public server.

To meet the requirement regarding reliability and semi-real-time, the operation time must be increased to guarantee a reliable link even in the rainy season. The main power drain is the CPU board, which provides the operation system and protocol processing function. Because the CPU board used in the first version is a general commercial piece, it includes a number of unnecessary items and attachments. The necessary functions of the proposed system are thus refined, and over-specified items, and attachments are deleted. The second version of the CPU board is shown together with the previous one in Fig. 5. The size of the new board is reduced to one-quarter of the original one, and the power consumption of the 250 mW transceiver with the new board is approximately 2 W. The improved operation time can then be calculated as

640 Wh/2 W \approx 320\text{ hours.} \quad (2)

That means that if fully charged, the remodeled high-power type device can operate for more than 10 days, which means that its reliability is greatly improved.

2) DEPLOYMENT OF REDUNDANT LINKS AMONG HIGH-POWER TYPE DEVICES

A pair of 20 mW devices was tested in a line-of-sight (LOS) environment to clarify the transmission distance. The two devices are both fixed at a height of 1.5 m above the ground. Antenna gain was 0 dBi, and the measured result was about 850 m. To reduce the number of required high-power type devices for capturing location data, all the 920 MHz transceivers of the signage devices in the buses were remodeled by increasing the transmission power from 20 to 250 mW. It is known that the propagation path-loss model can be expressed as

\[ \alpha = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 20\log_{10}(d), \quad (3) \]

where \( \alpha \) is the propagation path-loss in dB, \( \lambda \) is the wavelength, and \( d \) is the distance between the transmitter and receiver. By denoting the propagation distances of the 250 and 20 mW devices as \( d_{250} \) and \( d_{20} \), respectively, based on (3), the following holds:

\[ \alpha_{250} - \alpha_{20} = 20\log_{10}(d_{250}) - 20\log_{10}(d_{20}), \quad (4) \]

where \( \alpha_{250} \) and \( \alpha_{20} \) are the propagation path-losses of the 250 and 20 mW devices, respectively. Because the difference in transmission power is

\[ 10\log_{10}(250) - 10\log_{10}(20) \approx 10.97\,\text{dB}, \quad (5) \]

based on (4) and (5), \( d_{250} \approx 3.5d_{20} \). Taking into account the antenna gain of 5 dBi of the first version high-power type device with solar power and 4 dBi of the second version high-power type device, \( d_{250} \) is respectively 6.2\( d_{20} \) and 5.5\( d_{20} \). Therefore, propagation distance of more than 4.7 km in the LOS environment can be expected for the 250 mW transceiver.
2) LOCAL INFORMATION DELIVERY SERVICE
By using signage type devices, the gateway can transmit information to the bus version of signage type devices via the stationary version of signage type devices, which can increase life convenience for local residents. That is, some local services, such as local community events, local commercial advertisements, and local government public information, can also be distributed via signage type devices and shown on bus panels.

3) BUS LOCATION SERVICE
With signage type devices, by using the bus version of the signage type device, GPS information from buses can be transmitted to the gateway via high-power type devices, which can provide nearly real-time information on bus location to local residents; thus residents can confirm bus arrival information anytime and anywhere. Local residents can know when the bus will arrive at the nearest bus stop with a small little time error, which is a very convenient service.

4) SAFETY CONFIRMATION SERVICE
In some emergency cases, such as earthquakes, typhoons, or tsunamis, the normal cellular systems might already be destroyed; however, the government needs to confirm local emergency conditions. As the proposed system adopts distributed D2D communications that can avoid the risk of failure of the whole system, local residents can report their conditions to the government via links among UTs and high-power type devices. Therefore, the government can use the proposed system to confirm local resident safety information.

III. EXPERIMENTAL APPLICATION EVALUATION
For the applications and services listed in Sec. II-E that the proposed system aims to provide, the validation of the capabilities of the proposed system should be realized. To practically evaluate the real capabilities of the proposed system through field experiments, the proposed system was set up for the bus network in some parts of Kyoto and Tokyo in cooperation with local communities. The field experiments were conducted in Seika Town of Kyoto and the Odaiba area of Tokyo, the same areas as in Sec. III-D. The deployment maps of Seika Town and Odaiba are shown in Figs. 7 and 13, respectively. The Odaiba area is a typical urban area, whereas Seika Town is a typical rural area.

The following subsections describe the three experiments that validate the capabilities of the proposed system, which is necessary for implementation of the applications and services mentioned in Sec. II-E.

A. EVALUATION OF ENVIRONMENTAL INFORMATION SHARING SERVICE
To validate the performance of the environmental information sharing service, an experimental testbed was set for evaluating the multi-hop transmission of the proposed system in Seika-Town in Kyoto, as shown in Fig. 7. The concept of multi-hop transmissions of the proposed system is shown in Fig. 8. There are a maximum of four hops that can be used in this system. For example, sensor device S4 needs four hops to send its packets to the destination device, which is the fixed device connected to the Internet in Fig. 8, and the route is S4 → H4 → H3 → H1 → destination. However, the sensor device S1 needs only two hops to reach the destination with the route: S1 → H1 → destination.
To evaluate the performance of the frame design mentioned in Sec. II-D and shown in Fig. 6, the experiment is operated to test device transmissions using the MAC superframe structure pattern-I, -II, and -III, with the multi-hop settings in Fig. 8. The experimental results of the multi-hop transmission are shown in Fig. 9. From these results, the MAC superframe pattern-I can achieve the shortest packet transmission latency for all kinds of hop numbers, whereas the MAC superframe pattern-III always results in the longest packet transmission latency. The reason for this is that, compared with the other patterns, pattern-I can add more slots to sensor devices for transmitting their packets, which is how the packets can be successfully received earlier at the destination device.

B. EVALUATION OF LOCAL INFORMATION DELIVERY SERVICE

To evaluate the capability of information delivery of bus type devices, an experiment was set up to test device transmission by relaying with moving objects (buses). The experimental scenario is shown in Fig. 10 as follows: the device in Housono station, Kyoto, first receives information from the Internet and then sends it to moving buses running in Seika area; the devices in Town Hall, Kashinoki center and the National Laboratory receive the information from the devices on the buses. The aims of this experiment was to test the performance of the three MAC superframe patterns shown in Fig. 6 in a mobile environment. In this experimental scenario, the data size was increased by 0.2 kbytes for each test run, and the experiment then measured the maximum data size that could be successfully received per slot with different MAC superframe patterns. The results of this experiment are shown in TABLE 1. These results show that the MAC superframe pattern-III can result in the largest successfully received data size. Besides, to ensure the reliability of the designed MAC superframe patterns, the data size of 90% success rate was also listed for each MAC superframe pattern. Note that the data size ratio in TABLE 1 means the ratio of 90% success rate data size to the maximum data size, and the results of the three MAC superframe patterns are all about 96%.

C. EVALUATION OF BUS LOCATION SERVICE

To ensure that the proposed system can provide the bus location service within limited latency, the aim was to measure the coverage and delay performance of the proposed system. Here, the coverage performance is expressed and calculated by a coverage ratio which is defined by the number of packets received successfully by the devices on buses divided by the total number of sent packets. Therefore, an experiment with four high-power type devices H1–H4, was set up in Seika Town, Kyoto, as shown in Fig. 7. In the beginning, the coverage of the proposed system was measured when buses were moving; however, the coverage ratio of the proposed system was only 78%. Therefore, four more identical high-power type devices H5–H8 were added at the locations marked as “newly added hp-devices” on the map of Fig. 7, and the coverage ratio of the proposed system improved to 99.7%.

Besides, in the frame structure design mentioned in Sec. II-D and shown in Fig. 6, the characteristics and priorities of devices are not taken into account. To better utilize the proposed system, a new MAC superframe structure is...
designed, as shown in Fig. 11. In the frame structure shown in Fig. 11, in the beginning of the frame there is a short synchronization slot (sync). After the sync slot, there is a slot with a 4 sec time period for fixed devices, such as the devices deployed in buildings. Following the slot for fixed devices, there is another slot with a 4 sec time period for mobile devices, such as the devices installed on buses. Besides the slots for fixed and mobile devices, there are some short slots with a 2 sec time period for high-power types devices (H slot). The H slots are designed for high-power devices that can transmit signals with up to 250 mW power, and they are usually deployed on the rooftops of buildings. In the frame structure designed in this study, there are maximally eight but regularly seven high-power devices that can be accommodated. When there are eight high-power type devices, the eighth one sends its packet by using the first slot (the slot for fixed devices). All the slots are transmitted twice in the designed 60 sec frame structure to ensure that the packets of devices can be transmitted successfully, which means the maximal packet transmission latency is 60 sec. In addition, if there are portable devices and emergency services, their

### TABLE 1. Data sizes for different MAC superframe patterns.

| Pattern | I   | II  | III  |
|---------|-----|-----|------|
| Maximum Data Size (kbytes) | 19.8 | 25  | 30.4 |
| 90% Success Rate Data Size (kbytes) | 19  | 24  | 29.2 |
| Data Size Ratio | 96.0% | 96.0% | 96.1% |

**FIGURE 9.** Experimental results for multi-hop data.

**FIGURE 10.** Experiment scenario of bus relaying.
packets can occupy any slot in the 60 sec frame with high priority, as shown in Fig. 11. Note that the time period of high-power type devices is shorter than that of normal devices (fixed or mobile). The reason why the MAC superframe is designed in this way is because high-power type devices are used to send low-traffic but long-distance data; as a result, the time period of the slot can be reduced so that the MAC superframe can accommodate data from more devices.

With the newly designed MAC superframe shown in Fig. 11, Fig. 12 shows the experimental CDF of the time delay of the location data from all the other high-power type devices; that is, the data collected at H6 are used for marking bus locations. The analysis of collected data is summarized in TABLE 2. The time delay data are collected from 978 locations, and range from 5 to 132 sec. An average delay is about 41 sec, and 82.8% of data are within a 1 min delay. This coincides with the observation that the bus location is marked in less than a 1 min delay most of the time, which validates that the proposed design is effective.

**D. EVALUATION OF SAFETY CONFIRMATION SERVICE**

The evaluation of the performance of the safety confirmation service requires a large number of devices. However, the implementation of the proposed system with a large number of devices for experiments involves huge cost and effort. Therefore, some simulations were conducted to evaluate the performance of the proposed system in an urban area with a vast number of devices. In this section, the proposed system is assumed to work in an urban type of environment, namely the Tokyo area described in Sec. III-D.1. Details about the simulation setting and results are illustrated in the following subsections.

1) SIMULATION SETTINGS FOR URBAN AREA (TOKYO)

For the simulation in an urban area (Tokyo, Japan), it is assumed that there are three PTs for public use and 1000 active UTs for private use deployed in the Minato-Daiba area of Tokyo. The map of this area is shown in Fig. 13. The concept of the simulation for this area in Tokyo is shown in Fig. 14, which involves the simplified device deployment in the area shown in Fig. 13. The PTs are fixed at specified buildings (Atago Mori Tower, KM Tourist Office, and Odaiba Gakuen). The UTs are mobile, and there are 400 UTs near Odaiba Gakuen, 300 UTs near the Atago Mori Tower, and 300 UTs near the KM Tourist Office, which are uniformly distributed in a 3 km × 3 km area around each PT. The simulation parameters are listed in TABLE 3. In addition, this simulation involves the redesigned MAC superframe with an emergency mechanism, as shown in Fig. 11.

2) SIMULATION RESULTS

The simulation results regarding the reachability of the device safety confirmation message for the Tokyo area are shown in Fig. 15. The results show how many safety confirmation messages each UT can receive from other UTs. Fig. 15 shows that UT-Is (UT ID: 1-1000) can receive nearly 700 messages. This
means that 70% of the UTs can share the safety confirmation messages with each other in an urban area such as Tokyo, because all the links of the PTs are active. If one UT can connect to any PT, it can receive safety confirmation messages from the UTs in another group via the PT link. Otherwise it can only receive messages from the UTs in its own group. The reason why only 70% of the UTs can work in this case is, because the simulation takes the real propagation model of this area into consideration; therefore, the impact of path-loss and shadowing on each UT in an urban (Tokyo) area is quite strong and affects link performance. Owing to this impact, about 30% of UTs cannot connect to any PT in an urban area.

E. DISCUSSIONS

This study proposed a distributed local information sharing system based on D2D communication. To verify the feasibility and effectiveness of the proposed system, its capabilities were experimentally validated in application scenarios, and simulations with realistic information were performed to observe the behavior of the proposed system in a setting with a vast number of devices. The simulation results in Sec. III-D reflect the system situation according to the terrain and environment information. This means that although field experiments may not be conducted with a large number of devices owing to budget limitations, one can still obtain approximate system behavior through simulation and also obtain some important ideas from the simulation results when actually constructing a system that deploys a massive number of devices.

Besides, Sec. II-D, introduced the design of the MAC superframe, whose main goal is to ensure that the packet can reach the destination in a robust and low-latency way. The experimental results show that the proposed system can actually function in daily life. The latency of data transmissions in the proposed system is quite limited, and most of the packet delays (more than 80%) fall within 60 sec, which is consistent with the design idea of the proposed MAC superframe structure mentioned in Sec. II-D.

IV. CONCLUSION

This study proposed a novel system that can collect, distribute, and share local information. In the proposed system, devices can communicate with each other via D2D communications to form a network. In addition, a D2D testbed was developed to provide the system with green communication by lowering the power consumption and adopting a solar power supply. To evaluate the performance of the proposed
system, simulations and field experiments were conducted in two representative urban and rural areas in Japan. The results show that the proposed system can indeed automatically build a D2D network and that it can be implemented in real urban and rural areas, which validates its effectiveness and feasibility.

Nevertheless, although the proposed system is feasible and can function in the real world, it can still be improved to enhance the whole system performance, for example, by reducing the device discovery time, which is a task for future work.

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REFERENCES

[1] Study on Further Enhancements to LTE Device to Device (D2D), User Equipment (UE) to Network Relays for Internet of Things (IoT) and Wearables, document TR36.746. 3GPP 3rd Generation Partnership Project, v15.1.1 ed., Apr. 2018.
[2] J. Liu, C. Chen, and Y. Ma, “Modeling neighbor discovery in Bluetooth low energy networks,” IEEE Commun. Lett., vol. 16, no. 9, pp. 1439–1441, Sep. 2012.
[3] M. Conti, F. Delmastro, G. Minutillo, and R. Paris, “Experimenting opportunistic networks with WiFi direct,” in Proc. IFIP Wireless Days (WD), Nov. 2013, pp. 1–6.
[4] Z. Zhou, J. Gong, Y. He, and Y. Zhang, “Software defined machine-to-machine communication for smart energy management,” IEEE Commun. Mag., vol. 55, no. 10, pp. 52–60, Oct. 2017.
[5] G. Gui, F. Liu, J. Sun, J. Yang, Z. Zhou, and D. Zhao, “Flight delay prediction based on aviation big data and machine learning,” IEEE Trans. Veh. Technol., vol. 69, no. 1, pp. 140–150, Jan. 2020.
[6] J. Sun, W. Shi, Z. Yang, J. Yang, and G. Gui, “Behavioral modeling and linearization of wideband RF power amplifiers using BiLSTM networks for 5G wireless systems,” IEEE Trans. Veh. Technol., vol. 68, no. 11, pp. 10348–10359, Nov. 2019.
[7] Y. Wang, M. Liu, J. Yang, and G. Gui, “Data-driven deep learning for automatic modulation recognition in cognitive radios,” IEEE Trans. Veh. Technol., vol. 68, no. 4, pp. 4074–4077, Apr. 2019.
[8] H. Huang, Y. Song, J. Yang, G. Gui, and F. Adachi, “Deep-Learning-Based millimeter-wave massive MIMO for hybrid precoding,” IEEE Trans. Veh. Technol., vol. 68, no. 3, pp. 3027–3032, Mar. 2019.
[9] X. Sun, G. Gui, Y. Li, R. P. Liu, and Y. An, “ResiNet: A novel deep neural network with feature reuse for Internet of things,” IEEE Internet Things J., vol. 6, no. 1, pp. 679–691, Feb. 2019.
[10] B. Mao, F. Tang, Z. M. Fadlullah, N. Kato, O. Akashi, T. Inoue, and K. Mizutani, “A novel non-supervised deep-learning-based network traffic control method for software defined wireless networks,” IEEE Wireless Commun., vol. 25, no. 4, pp. 74–81, Aug. 2018.
[11] Z. M. Fadlullah, B. Mao, F. Tang, and N. Kato, “Value iteration architecture based deep learning for intelligent routing exploiting heterogeneous computing platforms,” IEEE Trans. Comput., vol. 68, no. 6, pp. 939–950, Jun. 2019.
[12] B. Mao, F. Tang, Z. M. Fadlullah, and N. Kato, “An intelligent route computation approach based on real-time deep learning strategy for software defined communication systems,” IEEE Trans. Emerg. Topics Comput., to be published, doi: 10.1109/TETC.2019.2894047.
[13] H. Huang, S. Guo, G. Gui, Z. Yang, J. Zhang, H. Sari, and F. Adachi, “Deep learning for physical-layer 5G wireless techniques: Opportunities, challenges and solutions,” IEEE Wireless Commun., pp. 1–9, 2019, doi: 10.1109/MWC.2019.1900027.
[14] H. Huang, Y. Peng, J. Yang, W. Xia, and G. Gui, “Fast beamforming design via deep learning,” IEEE Trans. Veh. Technol., vol. 69, no. 1, pp. 1065–1069, Jan. 2020.
[15] Z. Zhou, Y. Guo, Y. He, X. Zhao, and W. M. Bazzi, “Access control and resource allocation for M2M communications in industrial automation,” IEEE Trans Ind. Informat., vol. 15, no. 5, pp. 3093–3103, May 2019.
[16] Z. Zhou, M. Dong, K. Ota, G. Wang, and L. T. Yang, “Energy-efficiency resource allocation for D2D communications underlaying cloud-RAN-based LTE-A networks,” IEEE Internet Things J., vol. 3, no. 3, pp. 428–438, Jun. 2016.
[17] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, “Device-to-device communication as an underlay to LTE-advanced networks,” IEEE Commun. Mag., vol. 47, no. 12, pp. 42–49, Dec. 2009.
[18] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Mikkol, and Z. Turányi, “Design aspects of network assisted device-to-device communications,” IEEE Commun. Mag., vol. 50, no. 3, pp. 170–177, Mar. 2012.
[19] A. Ghosh, N. Mangalvedhe, R. Ratasuk, B. Mondal, M. Cudak, E. Visotsky, T. A. Thomas, J. G. Andrews, P. Xia, H. Shin Jo, H. S. Dhillon, and T. D. Novlan, “Heterogeneous cellular networks: From theory to practice,” IEEE Commun. Mag., vol. 50, no. 6, pp. 54–64, Jun. 2012.
[20] K. Zou, M. Wang, K. Yang, J. Zhang, W. Sheng, Q. Chen, and X. You, “Proximity discovery for device-to-device communications over a cellular network,” IEEE Commun. Mag., vol. 52, no. 6, pp. 98–107, Jun. 2014.
[21] M. Liu, J. Yang, and G. Gui, “DSF-NOMA: UAV-assisted emergency communication technology in a heterogeneous Internet of things,” IEEE Internet Things J., vol. 6, no. 3, pp. 5508–5519, Jun. 2019.
[22] H.-B. Li, R. Miura, and F. Kojima, “A study on quick device discovery for fully distributed D2D networks,” IEICE Trans. Commun., vol. E101-B, no. 3, pp. 628–636, 2019.
[23] 920 MHz-Band Telemeter, Telecontrol, and Data Transmission Radio Equipment, document STD-T108, Association of Radio Industries and Businesses (ARIB), 1st ed., Feb. 2012.
[24] H.-B. Li, L. Shan, T. Matsuda, and R. Miura, “Design and deployment of infrastructure-independent D2D networks without centralized coordination,” in Proc. Int. Symp. Wireless Commun. Syst. (ISWCS), Brussels, Belgium, Aug. 2015, pp. 376–380.

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