2-7 Development and Field Trial of D2D Networks for Local Area Information Collection and Distribution

Huan-Bang LI, Lin SHAN, Ryu MIURA, Takashi MATSUDA, Fumihide KOJIMA,
Yasunori OWADA, and Masugi INOUE

NICT has developed a testbed of device-to-device communication networks for the purposes of information collection and distribution among local communities. With the cooperation of local administrations, the testbed was deployed in the Odaiba area of Minato City of Tokyo as well as in Seika Town of Kyoto, respectively, in 2014. The Odaiba area and Seika Town are respectively used as a typical urban model and a typical rural model. All devices of the testbed are installed at 920 MHz frequency band. On one hand, various devices of the testbed are installed in the community buses including 'Odaiba Rainbow Buses' operated by Minato City as well as 'Seika Kururin Buses' operated by Seika Town. On the other hand, devices of the testbed are deployed in the surroundings of bus routes. Various experiments have been being conducted since then. None of devices performs central coordination in the testbed. Devices communicate each other autonomously when they are within communication range. Consequently, any single device doesn't have dominant effect to the entire network. Such features enable robust communication networks during emergency situation such as disasters. Devices installed in buses communicate with surrounding devices anywhere within range and exchange information each other, so that local area information are collected and distributed as buses move. Moreover, by receiving the location information sent from the running buses across all bus routes, we construct a bus location guidance system. The developed device-to-device communication networks for information sharing at local community are independent from cellular and other existing wireless networks and various applications can be expected.

1 Introduction

While the standardization on device-to-device (D2D) communications is underway within 3GPP [1] and IEEE802 [2], various research efforts are being made to develop D2D which is regarded as a component of the heterogeneous network [3]–[6]. Research is being conducted to develop D2D communication systems that leverage existing infrastructure, including a part of cellular networks [4][5], and autonomous D2D communication systems, such as a peer aware communication (PAC) network [6]. Direct communications between devices may reduce wireless network load, including that in cellular networks, and increase communication speed between transmission and reception antennas. In addition, they are useful in increasing throughput in hotspots. Furthermore, research is being conducted on the role of D2D communications in IoT and mobile social networks [7][8].

We developed D2D communication network testbeds by focusing on areas where community buses are operated to facilitate local information sharing by the public using a broadcasting mode as a basic communication technique [9][10]. With the collaboration of Minato City, Tokyo and Seika Town, Kyoto, we set up our testbeds in these areas and carried out demonstration experiments there from 2014. The testbeds included the Odaiba Rainbow Bus, a community bus service run by Minato City, the Seika Kururin Bus, a community bus service run by Seika Town, and the routes of these bus services. Information was transmitted between communication devices installed in buses and communication devices within the test terminals installed along the bus routes while the buses were in operation. A variety of community-related information, such as local government information and event announcements, was collected and diffused in these experiments. We later added redundancy to the testbed in Seika Town, enabling collection of bus location data sent from the communication devices installed in Seika Kururin buses when the buses are traveling along their service routes. This information was used to make bus location notification service available to the public.

We describe below the characteristics of the D2D communication system we developed, the structure of test terminals installed in the testbeds, testbed operations and the demonstration experiments we conducted. We explain these mainly using the D2D communication testbeds in their forms as of July 2017.

2 Concept and characteristics of D2D communication

The concept of the D2D communication system we developed is illustrated in Fig. 1. We developed various types of test terminals, including signage terminals, rooftop terminals and sensor terminals. They are composed of communication devices for data transmission and reception, peripheral devices and interfaces such as displays that meet the purposes of each test terminal. From a network configuration standpoint, we developed systems that are not centrally controlled by any terminal or device, and in which all communication devices perform the same functions. When a communication device transmits information, it does so using a predetermined time slot and a broadcasting mode specified in the communication protocol mentioned below. Other communication devices within range receive the broadcasted information.

A communication device set in a signage terminal installed in a bus repeatedly transmits and receives data while it is travelling to/from other test terminals installed along the bus routes. This communication method enables travelling buses to repeatedly update and provide various types of community-related information such as local government information, event information and advertisements, within the local community. The effectiveness of the method depends on the bus service area size and bus service frequency.

The D2D communication system is not centrally controlled and autonomously establishes a network between communication devices existing within communication range. Therefore, additional communication facilities, such as base stations, are unnecessary. In addition, the system is resistant to natural disasters because failure of some communication devices in the network only slightly affects the entire network. Moreover, the D2D communication system has the following additional characteristics.

(1) Autonomous communication protocol and GPS-based synchronization

Communication protocols must be determined in advance so that the devices within communication range can autonomously communicate with each other. We first decided that all devices would use the same frequency channel so they can quickly detect signals transmitted from each other. When the number of communication devices exceeds

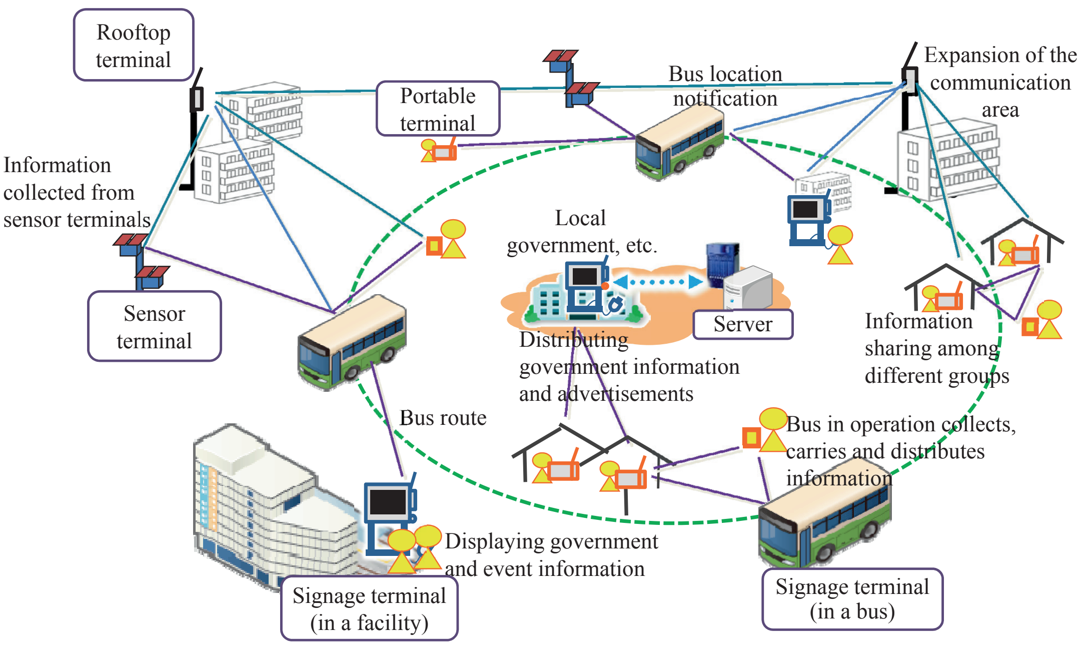


Fig. 1 Conceptual illustration of the D2D communication network

the channel capacity, it is still feasible for the communication devices to quickly detect each other using the method we proposed which employs several different frequency channels [11]. We then configured a transmission frame within which transmission time slots were assigned to each communication device installed in a test terminal. The time slot assignment took into account the role each terminal plays. This process ensured that signals transmitted from communication devices properly diffuse. Within the transmission frame, we determined time slot duration and transmission frequency for each communication device while taking into account the role of each test terminal which houses the communication device. The communication devices are capable of transmitting data only during their assigned time slots (a frame structure example is shown in Fig. 7). In our system, the transmission frame duration was set to be 60 seconds and this cycle was repeated. We installed GPS receivers in all test terminals distributed across the experimental area in order to enable them to receive time pulses transmitted from GPS satellites and thereby achieve transmission frame synchronization. Some test terminals installed inside buildings were unable to receive GPS signals. Accordingly, we synchronized these terminals by arranging other terminals—which have been synchronized using GPS time pulses—to send synchronization signals to them.

(2) TDMA- and CSMA/CA-based channel access schemes

All communication devices—which use the same frequency channel as described in the previous section—access the channel primarily using a TDMA (time-division multiple access) scheme appropriate for these types of devices. However, when multiple test terminals of the same type are within communication range, data packets transmitted from them might collide. To avoid this, we also adopted a CSMA/CA (carrier sense multiple access with collision avoidance) scheme in addition to TDMA. The scheme allows a communication device to transmit data only when no other device is doing so. The combined use of TDMA and CSMA/CA enables communication devices in different types of test terminals to autonomously establish a communication network between them.

(3) Information buffering function

Mutual communications between terminals are possible only when they are within communication range. To increase the number of terminals that can share information, we added an information buffering function to the terminals. When a terminal receives data packets, the data packets are stored in a buffer for a certain time period. If a new communication terminal enters communication range during this time period, the stored data packets are transmitted to the entered terminal. In our system, communication devices shift their locations, causing information propagation routes to change continuously. Under this condition, a communication device might receive the same data packets multiple times. To prevent this, we assigned a unique ID to each data packet to make it distinguishable. In addition, a communication device might receive old data packets in correlation with the network routes that the data packets followed. To avoid this, we attached time information to each data packet so as to update them accordingly and continuously.

3 Structure of test terminals in the testbed

While various types of test terminals are used in the testbed, they all operate at 920 MHz, which is a specified frequency band defined in the ARIB STD T108 standard [12]. We are using either 20 mW (which can be used without a license) or 250 mW (which can be used upon being registered) communication devices depending on their usage. Both types can be used free of communication fee. The power difference in decibels between these two types of communication devices can be calculated using the following equation.

$$10\log(250) - 10\log(20) \approx 10.97dB \tag{1}$$

This difference can be converted into the difference in propagation distance using the following equations which take into account the propagation loss in free space.

$$\mathrm{L(dB)} = 20\log\left(\frac{4\pi}{\lambda}\right) + 20\log(D) \tag{2}$$

$$\mathrm{L}_2(dB) - \mathrm{L}_1(dB) = 20\log(D_2) - 20\log(D_1) \tag{3}$$

Through the calculation, it was found that the difference in propagation distance between the 20 mW and 250 mW communication devices was $D_2 \approx 3.5 \times D_1$, given that the same type antenna was used.

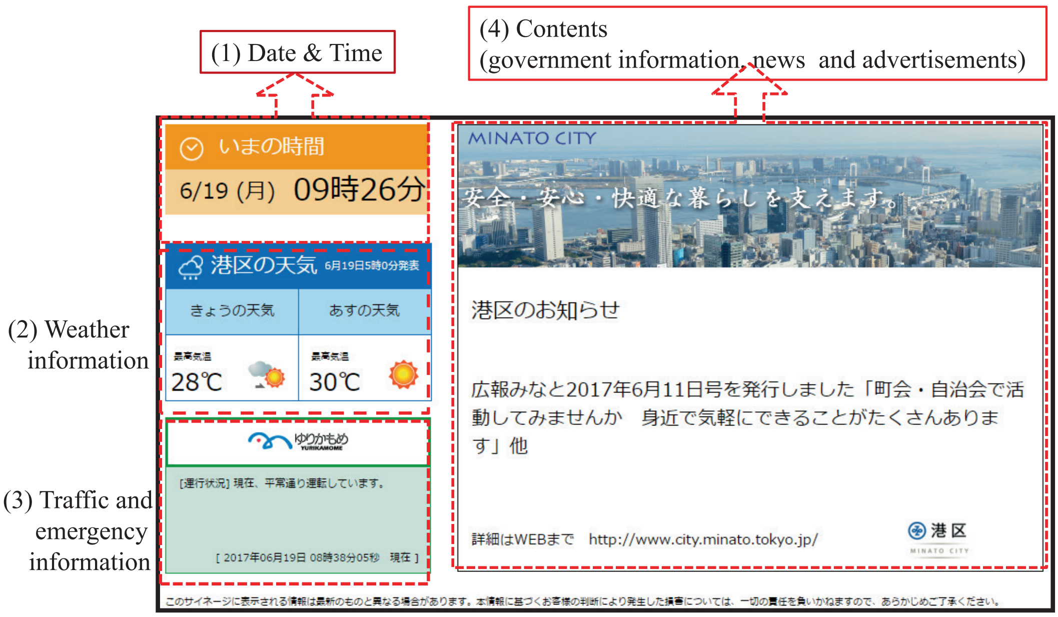
The signal bandwidth of both communication devices was 400 kHz. They both employed the GFSK modulation and the CRC-16 error-detecting code. Their transmission rate was 115,200 bps. We describe below the role of each type of test terminal we developed.

3.1 Signage terminal

An example of a display of the signage terminal is shown in Fig. 2 (a). The display consists of four informational sections which exhibit (1) time and date, (2) weather information, (3) traffic and emergency information and (4) the “contents” information including local government-related information, news, events and advertisements. The contents information can be either obtained from local government office websites, or input manually by users. One type of signage terminal (S-F terminal) was placed at public facilities, such as a government office (Fig. 2 (b)), and the other type (S-B terminals) in buses (Fig. 2 (c)). An S-B terminal in a travelling bus updates the information it displays as the communication device in the terminal exchanges information with other terminals entering communication range. On the other hand, an S-F terminal updates the information it displays as it receives new information from S-B terminals. In principle, both the S-B and S-F terminals operate at 20 mW. The exception to this is that we installed 250 mW communication devices in the Seika Kururin buses in order to put into practice the bus location notification service described below. All signage terminals are equipped with a built-in GPS receiver.

3.2 Rooftop terminal

Rooftop terminals refer to test terminals placed in high places, such as on the top of buildings. They can be used to expand the communication range so as to improve net-

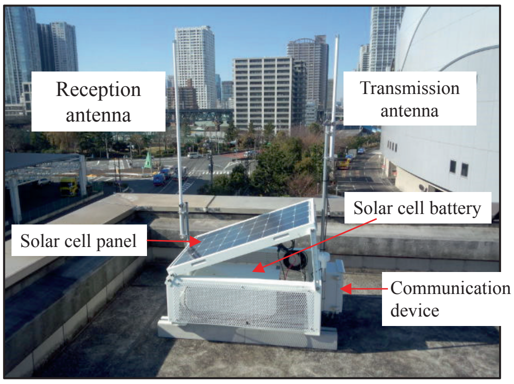


(a) Signage display

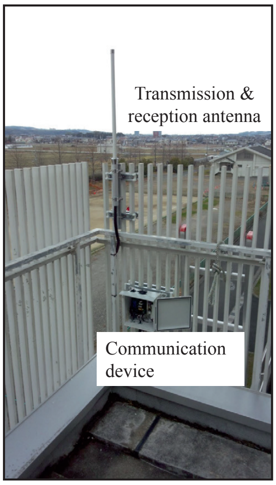
(b) Signage terminal at a public facility

(c) Signage terminal behind a bus driver seat

Fig. 2 Signage terminal examples



(a) Standalone rooftop terminal



(b) Simple rooftop terminal

Fig. 3 Examples of installed rooftop terminals

work connectivity. For these purposes, all rooftop terminals operate at 250 mW. We developed two types of rooftop terminals: standalone rooftop terminals powered by solar batteries, which can operate on the top of buildings where no high-voltage public outlet is available and in times of natural disasters, and simple rooftop terminals that can be installed easily in places where high-voltage public outlets are available. The standalone rooftop terminal and the simple rooftop terminal are shown in Fig. 3 (a) and (b), respectively.

A standalone rooftop terminal is powered by a solar cell system with a maximum capacity of 640 Wh, and the communication device attached to the terminal consumes approximately 2 W of power. The number of hours the terminal can operate continuously can be calculated using the following equation, assuming that the solar cell system is charged to 80%.

$$640 \text{ Wh} \times 80\ \% \ / \ 2 \text{ W} = 256 \text{ h} \tag{4}$$

This result indicates that the communication device is capable of continuous operation for more than 10 days so that it can operate stably even under adverse weather conditions, such as during a rainy season. On one hand, the standalone rooftop terminal is equipped with two separate antennas for data transmission and reception. On the other hand, the simple rooftop terminal is equipped with only a single antenna capable of both data transmission and reception for easier installation. Rooftop terminals are capable of communicating with each other and receiving bus GPS data and sensor data transmitted from the sensor terminals described in the next section. The rooftop terminals are also equipped with a built-in GPS receiver.

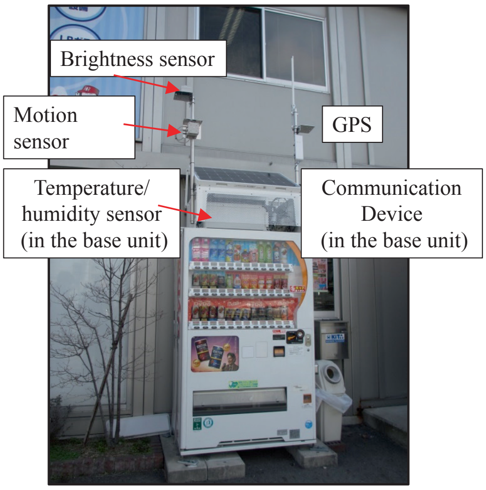


Fig. 4 Example of a sensor terminal mounted on a vending machine

3.3 Sensor terminal

A sensor terminal (Sen) is equipped with temperature, humidity, brightness and motion sensors and a GPS receiver. Like the standalone rooftop terminal, we also attached a solar cell system to the sensor terminal in order to make it operable at many outdoor locations. An example of a sensor terminal mounted on a vending machine is shown in Fig. 4. A sensor terminal operates at 20 mW and transmits data collected by its sensors to rooftop terminals and communication devices in buses entering communication range. We designed the sensor terminals to be capable of only data transmission and not reception to make them energy efficient.

We also developed portable terminals for use in various demonstration experiments. However, we installed them in our testbeds only temporarily. Therefore, we omitted them in this paper.

4 Testbed operations and demonstration experiments

4.1 Testbed operations and demonstration experiments in an urban environment: Odaiba Rainbow Bus (Minato City, Tokyo)

We chose the Odaiba area—in which the Odaiba Rainbow Bus service operates—as our urban environment setting and set up our testbed there. A schematic diagram of the testbed established around the Odaiba Rainbow Bus route is shown in Fig. 5. Seven Odaiba Rainbow buses operate along the route which starts from Shinagawa Station or Tamachi Station, crosses the Rainbow Bridge and goes through the Odaiba area. Eleven 20 mW signage terminals were installed in seven buses, the Minato City Office and other facilities in the Odaiba area, including the Fuji Television Building. Tall buildings in the urban environment block radio waves and cause multipath propagation. Community buses typically operate in this type of environment. We conducted an information sharing experiment in this urban setting in which information was collected and distributed between the Odaiba Rainbow buses and the facilities around the Odaiba area. The following information was collected and diffused in our experiment: Minato City government information, Fuji TV news, event information for the Grand Nikko Tokyo Daiba and traffic information from the KM Kanko Bus [13]. Because these buses did not travel in areas near the Minato City Office, we made an arrangement so that the information from the Minato City Office was transmitted via the Internet to the signage terminal at the Fuji Television Building. The terminal then transmitted the information to the buses. We confirmed that the information was frequently updated as the Odaiba Rainbow buses traveled periodically along the route.

In addition, we also confirmed that the five rooftop terminals established a communication link across the sea area (Fig. 5). The five rooftop terminals installed with 250 mW communication devices were powered by solar cell systems. Links were established between them for emergency use. Although the transmission frames designed for these links were only able to transmit a smaller amount of information than those transmitted to and from buses, they were capable of fast transmission. An example of the transmission frame is illustrated in the next section. We also established communication links using the rooftop terminals which enabled emergency transmission from the Minato City Office.

4.2 Testbed operations and demonstration experiments in a suburban environment: Seika Kururin Bus (Seika Town, Kyoto)

We chose Seika Town—in which the Seika Kururin Bus service operates—as our suburban environment setting and set up our testbed there. A schematic diagram of the testbed established around the Seika Kururin Bus routes is shown in Fig. 6. We installed eight signage terminals, eight rooftop terminals and six sensor terminals in the area. As

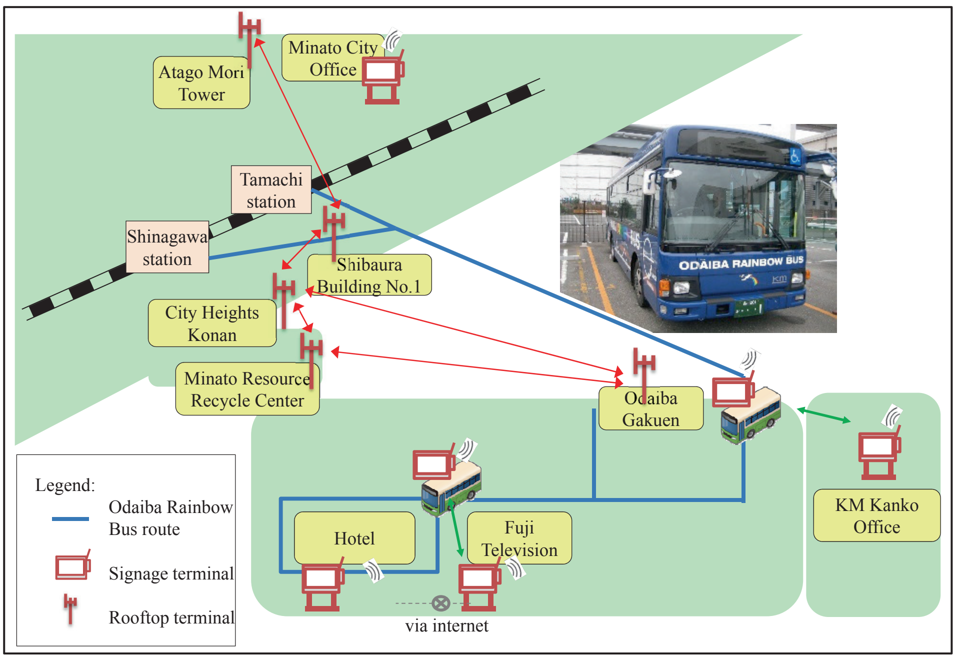


Fig. 5 Testbed established around the Odaiba Rainbow Bus route

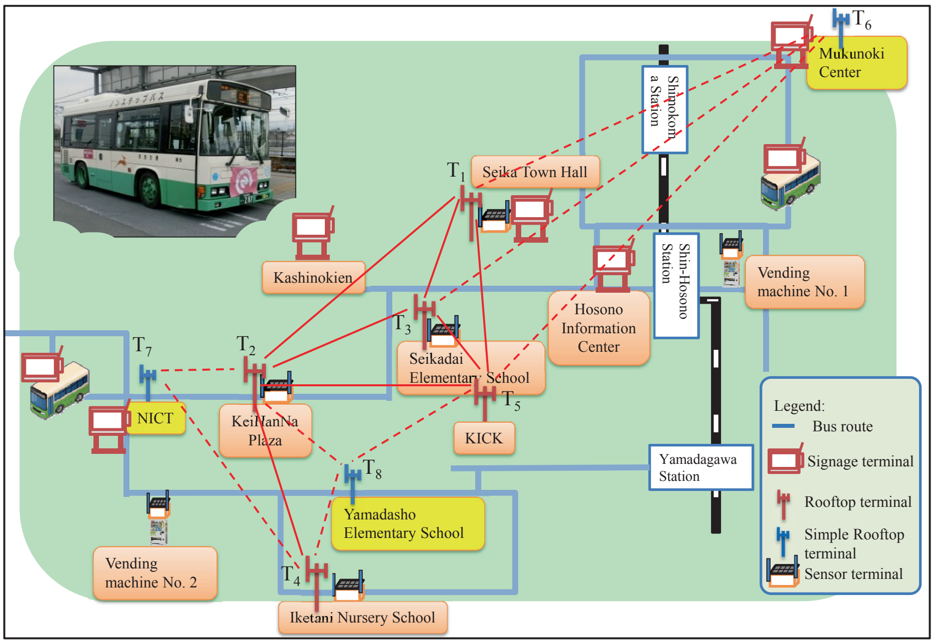


Fig. 6 Testbed established around the Seika Kururin Bus line

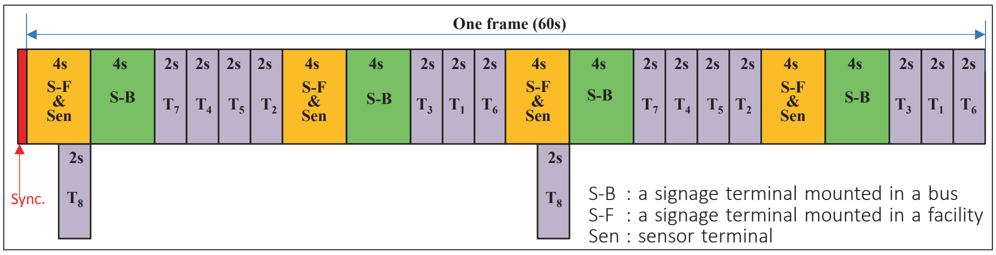


Fig. 7 Transmission time frame example

described in Subsection **3.3**, a sensor terminal only transmits data it acquired via the sensors attached to it. A total of eight signage terminals were installed in three Seika Kururin buses (including one back-up bus) and five facilities in the area, including the Seika Town Hall. The following information was collected and distributed in our experiments using Seika Kururin buses: government-related information from the Seika Town Hall, event information from the Kansai-kan of the National Diet Library and traffic information from Nara Kotsu Bus Lines [14]. We noticed that there were strong public demands for the Seika Kururin Bus to provide bus location notification service due to infrequent community bus operations in the suburban environment of Seika Town. To put this service into practice, it was necessary to grasp the location data of all buses in operation across the Seika Kururin Bus routes in semi-real time. Therefore, we installed 250 mW communication devices in three Seika Kururin buses to enable transmission signals from these buses to travel farther distances.

In addition, we installed three simple rooftop terminals in the testbed in addition to the five standalone rooftop terminals already respectively installed on the top of the Seika Town Hall building and at the other locations (Fig. 6). This arrangement enabled these rooftop terminals to receive bus location data transmitted from arbitrary locations along the bus routes. For convenience of description, we named the eight rooftop terminals T_1 through T_8 in Fig. 6. The addition of the three simple rooftop terminals (T_6, T_7 and T_8) reinforced coverage over the Seika Kururin Bus routes as shown by dotted lines in Fig. 6. The addition also increased redundancy in the rooftop terminal network. As a result, each rooftop terminal established two to six links with other rooftop terminals, which strengthened bus location data sharing between the terminals (Fig. 6). The range of coverage may become smaller if high-voltage public outlets become unavailable for some reason. However, the network established among the five standalone rooftop terminals (indicated by solid red lines in Fig. 6) can maintain operation.

An example of the transmission frame structure used in the testbed established around the Seika Kururin Bus route is shown in Fig. 7. A transmission frame is 60 seconds in duration and synchronized to time pluses from GPS satellites. It is composed of multiple time slots assigned to the test terminals.

In the frame, we first assigned four almost equally spaced four-second time slots to signage terminals installed in buses (S-B) to allow these terminals to transmit data frequently. When two or more buses exist in communication range, the CSMA/CA scheme is used to autonomously avoid data packet collisions. We then assigned time slots—similar to those assigned to the signage terminals in buses—to both signage terminals installed in facilities (S-F) and sensor terminals (Sen). We made this arrangement because both S-F and sensor terminals were stationary and can be installed outside communication range. If S-F and sensor terminals happen to enter communication range, the CSMA/CA scheme is used to establish autonomous communications between these terminals, as with the S-B terminals mentioned above. Because rooftop terminals covered a larger area than the other types of terminals mentioned above and neighboring rooftop terminals need to communicate with each other to relay data, we assigned a time slot of two seconds respectively to each rooftop terminal. Rooftop terminals were designed to transmit and receive bus location data, data collected by sensors and emergency information; but not to transmit or receive the “contents” data.

Seika Kururin buses in operation transmit their location data to rooftop terminals that are within their communication range. The rooftop terminals then share the data among themselves via the network established. An example of measurements of delay in bus location data transmission is shown in Fig. 8. Without loss of generality, Seika Kururin buses transmitted their location data at arbitrary locations along the bus route to rooftop terminals within communication range. The location data was then relayed to the T_6 rooftop terminal on top of Mukunoki Center (Fig. 6). Therefore, the transmission delay is the time it takes for the bus location data to travel from a bus to T_6 rooftop terminal. Transmission delay of bus location data was mostly within 60 seconds, but occasionally exceeded 120 seconds.

The results of transmission delay data analysis are shown in Table 1. Transmission delay was within 60 seconds for 82.8% of datasets and within 120 seconds for 99.7% of datasets. In other words, the current location of a Seika

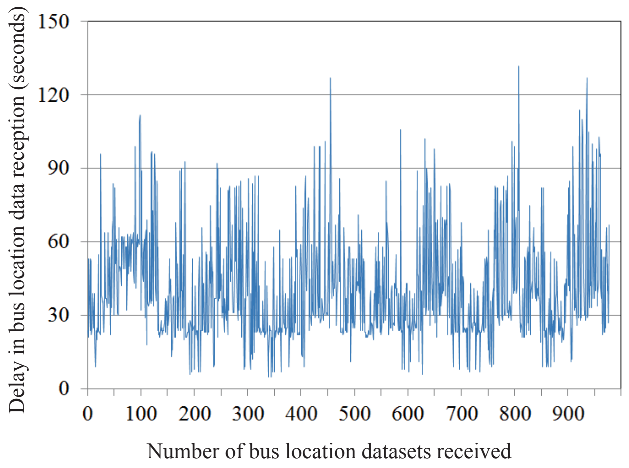


Fig. 8 Example of measurements of delay in bus location data transmission

Table 1 Results of transmission delay data analysis

Delay (seconds)	5–30	31–60	61–120	120–132
Number of datasets	412	398	165	3
Percentages	42.1%	40.7%	16.9%	0.3%
Cumulative percentages	42.1%	82.8 /%	99.7%	100%

Kururin bus can be collected within two minutes most of the time, and it can be detected within a minute 82.8% of the time.

5 Conclusion

This paper described the D2D communication testbeds with no central control function we developed and their operation and demonstration. The testbeds deployed in Minato City, Tokyo and Seika Town, Kyoto have been operating without problems, effectively collecting and distributing local information and facilitating information sharing in local communities. In the suburban environment of Seika Town, the simple D2D communication system used in our testbed enabled provision of a bus location notification service. In addition, the system can be operated free of communication fees and is therefore easy to introduce.

Although we did not mention it in this paper, we were able to establish coordination between the D2D communication system and external servers of Minato City during our demonstration experiment. We were also able to distribute emergency information related to Minato City across the testbed area. In addition, the demonstration experiment in Seika Town confirmed the usefulness of the bus location notification service. Accordingly, we plan to experimentally make the service available to the public.

The D2D system we developed can be operated without obtaining a license required under the radio wave law, is resistant to mechanical failure and natural disasters and is capable of easily collecting and distributing information from traveling buses, although delay occurs during data transmission. We hope to further explore the system utilization.

Acknowledgment

We thank Minato City, Tokyo and Seika Town, Kyoto and other organizations for their cooperation in the testbed operation and demonstration experiments.

References

1 http://www.3gpp.org/about-3gpp
2 http://www.ieee802.org/15/pub/TG8.html
3 A. Ghosh, et al., "Heterogeneous cellular networks: From theory to practice," IEEE Comm. Mag., vol.50, no.6, pp.54–64, June 2012.
4 K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," IEEE Comm. Mag., vol.47, no.12, pp.42–49, 2009.
5 K. J. Zou, M. Wang, K. W. Yang, J. Zhang, W. Sheng, Q. Chen, and X. You, "Proximity discovery for device-to-device communications over a cellular network," IEEE Comm. Mag., vol.52, no.6, pp.98–107, June 2014.
6 M. Lee, H.-B. Li, and S.-H. Park, "Introduction to Peer Aware Communications (PAC)," https://mentor.ieee.org/802.15/documents?is_dcn=pac&is_group=wng0&is_year=2012.
7 O.Bello and S. Zeadally, "Intelligent Device-to-Device Communication in the Internet of Things," IEEE Systems Journal, vol.10, no.3, pp.1172–1182, 2016.
8 J. Lee, T.Q.S. Quek, "Device-to-Device Communication in Wireless Mobile Social Networks," 2014 IEEE 79th Vehicular Technology Conference (VTC Spring), May 2014.
9 H.-B. Li, L. Shan, T. Matsuda, and R. Miura, "Design and deployment of infrastructure-independent D2D networks without centralized coordination," International Symposium on Wireless Communication Systems (ISWCS2015), Brussels, Belgium, Aug. 2015.
10 H.-B. Li, L. Shan, R. Miura, and F. Kojima, "D2D Networks for information diffusion and bus location gaining with local community buses," (Invited Paper) IEEE 85th Vehicular Technology Conference (VTC-spring 2017), Sydney, Australia, June 2017.
11 H.-B. Li, R. Miura, and F. Kojima, "Channel access proposal for enabling quick discovery for D2D wireless networks," International Conference on Computing, Networking and Communications (ICNC 2017), Santa Clara, CA, USA, Jan. 2017.
12 ARIB STD-T108 Version 1.0, "920MHz-band Telemeter, Telecontrol and Data Transmission Radio Equipment," Association of Radio Industries and Businesses Feb. 2012.
13 https://www.km-bus.tokyo/route/odaiba/
14 http://www.narakotsu.co.jp/rosen/index.html

Huan-Bang LI, Dr. Eng.
Chief Senior Researcher, Wireless Systems Laboratory, Wireless Networks Research Center
Wireless communication, Mobile communication, Device-to-Device (D2D), Ultra-Wide Band (UWB)

Lin SHAN, Ph.D.
Researcher, Wireless Systems Laboratory, Wireless Networks Research Center
Wireless communication, Mobile communication, Device-to-Device (D2D), Unmanned Aircraft System (UAS)

Ryu MIURA, Dr. Eng.
Executive Researcher, Wireless Networks Research Center
Mobile communication, Wireless control communication

Takashi MATSUDA, Dr. Eng.
Researcher, Wireless Systems Laboratory, Wireless Networks Research Center
Wireless sensor network, Wireless power transmission, Body area network

Fumihide KOJIMA, Dr. Eng.
Director, Wireless Systems Laboratory, Wireless Networks Research Center
Wireless communcation, Wireless access control

Yasunori OWADA, Dr. Eng.
Senior Researcher, Applications Laboratory, Resilient ICT Research Center
Distributed system, Wireless access network

Masugi INOUE, Dr. Eng.
Director, International Research Advancement Office, Global Alliance Department
Wireless network