Bringing Movable and Deployable Networks to Disaster Areas: Development and Field Test of MDRU

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***Abstract*—The communication demand is paramount for disaster-affected people to confirm safety, seek help, and gather evacuation information. However, the communication infrastructure is likely to be crippled due to a natural disaster that makes disaster response excruciatingly difficult. Although traditional approaches can partially fulfill the most important requirements from the user perspective, which includes prompt deployment, high capacity, large coverage, useful disaster-time application, and carrier-free usability, a complete solution that provides all those features is still required. Our collaborative research and development group has developed the Movable and Deployable Resource Unit, which is referred to as the MDRU and has been proven to have all those required features. Via extensive field tests using a compact version of MDRU, i.e., the van-type MDRU, we verify the effectiveness of the MDRU-based disaster recovery network. Moreover, we demonstrate the further improvement of MDRU's performance when it is complemented by other technologies such as Relay-by-Smartphone or satellites.**

***Index Terms*—Disaster resilient network, Movable and Deployable Resource Unit, MDRU.**

I. Introduction

In recent years, humans have to deal with dire consequence of many disasters that caused immeasurable influence on our life [1]. Specially, Japan is one of the countries facing the most disasters in the world. The great east Japan earthquake in 2011 caused the catastrophic impact on lives. Besides, the typhoon Haiyan in Philippines in 2013, the Haiti earthquake in 2010, the great Sichuan earthquake in China in 2008, and the Hurricane Katrina in the United States in 2005 are recent examples of how natural disasters affects our life. The common observation with all these afore-mentioned disasters is the fact that whenever there is a disaster, the natural reaction is to send relief there. The traditional sense of sending relief is dispatching money, food, medicine, and clothes to the disaster victims. Let us extend this notion of sending relief in the sense of communication support. When the communication infrastructure collapses in the disaster site, the victims are in dire need to communicate with others to confirm their safety, seek help, and gather evacuation information. Therefore, to support the disaster victims' communication needs, the authority should dispatch some resource units to provide them with "communication relief". With this motivation in mind, the collaborative research and development group launched by the Nippon Telegraph and Telephone (NTT) Corp., Tohoku University, NTT Communications Corp., and Fujitsu Corp. envisioned, for the first time, a complete resource unit based solution for providing communication services in the disaster-stricken area. The concept of that special resource unit is called Movable and Deployable Resource Unit, which is referred to as MDRU [2], [3]. The idea of the MDRU is to rapidly transport the resource unit to the disaster site and configure a recovery network, which provides network services to users in the area.

In contrast with our previous work in [2] that introduced the basic concept of MDRU and its system design, in this article, we aim to demonstrate our newest implemented MDRU, and the conducted field tests using this latest version. This version of MDRU is a van-type resource unit, which is capable of carrying all necessary equipment to promptly construct a disaster recovery network in disaster areas. Since the van-type MDRU itself is agile while the equipment inside the van-type MDRU is modularized to be portable equipment, it can be applied to many different scenarios of disasters. The conducted field tests verify the performance of the disaster recovery network based on the van-type MDRU. Furthermore, the successful connections to smartphones using Relay-by-Smartphone [4] and satellites using WINDS [5] show the extendability of the MDRU-based disaster recovery network.

The remainder of this paper is organized as follows. Section II outlines existing research works that are related to disaster recovery techniques. Section III answers the question why MDRU is needed for recovering communication services in disaster areas. After that, the most important required features of MDRU are presented in Section IV. In Section V, we introduce the latest achievement of our project, a van-type MDRU, which is compact, agile, yet capable of providing required features. The most typical application provided by MDRU is also introduced in this section. Section VI describes the testbed-based experiments conducted in real field. In Section VII, the future directions using the concept of MDRU

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and recovery network are introduced. Finally, Section VIII concludes the paper.

II. Relevant Research Works

Due to the great impact of disasters on the communication infrastructure, that causes a significant influence on disaster response, many research aspects related to disasters and communications could be found in literature. Even though many researchers have stressed on the planning and preparation of communication technology or the necessity of the redundancy in designing communication infrastructure [6], [7], post disaster response has also attracted significant attention [8]–[11]. Some of the existing works on post disaster response have focused on situation management and the support for disaster responders. For example, George *et al.* [8] proposed the DistressNet, which is a wireless ad-hoc and sensor network architecture aiming to improve the situational awareness. Pace and Aloi [9] focused on utilizing space technologies and satellite applications to monitor the disasters and mitigate their effects. On the other hand, many different works aimed to make a more effective response to disasters. While 911-network on wheels (911-NOW) proposed by Abusch-Magder *et al.* [10] attempted to use the network on wheels technology to make a portable cellular system, Jun *et al.* [11] concentrated on more service-oriented architectures to support disaster response. Relay-by-Smartphone [4] can be also considered as a solution for the communications demand in the disaster area. The main idea of Relay-by-Smartphone is to utilize only Wi-Fi functionality of smartphones to relay messages between the devices. Therefore, when the cellular network is out of service due to the effect of disaster, this technology can be used to make the communications between people possible. Since the above-mentioned works only consider one part of the whole solution for disaster response, a more complete solution needs to be taken into account, that includes deploying networks, providing and managing services, and so forth.

To complement the afore-mentioned researches carried out in academia, industry driven efforts are also worth noting. For example, NTT in Japan has focused on preventing the effects of disasters on their telecommunication network for more than twenty years [12]. Three fundamental principles, namely improving network reliability, preventing isolation, and rapidly restoring services, have been considered in their efforts to make NTT networks more resilient to disasters. However, only users using the NTT carrier may be benefited from those efforts. A more "carrier-free" solution might be needed for the general disaster response.

III. Problem Formulation: Why is MDRU Needed?

Right after the great east Japan earthquake in 2011, the telecommunication carriers experienced an explosive increase of demand for services. People attempted to use communication services to confirm the safety of their family, relatives, and friends. The government and companies also rushed to use services for management. However, due to the outage of electric power, the damages of information and communications resources, and other reasons, services and resource supplies went down significantly. It resulted in a critical gap between service supply and demand. In order to relax the situation, traditional approaches using ad-hoc networks, wireless mesh networks, delay/disruption tolerant networking (DTN), or satellites were considered for use in the disaster areas. Indeed, each of them has its own strong points, but is still prone to significant shortcomings, as depicted in Fig. 1. For example, ad-hoc networks, mesh networks, and DTN are relatively easy to be configured even in disaster areas. However, while DTN and ad-hoc networks can be constructed by using only user devices, mesh networks required remaining infrastructure to be set up. The main disadvantage of DTN is the long communication delay while that of ad-hoc networks is the limited number of users. Both DTN and ad-hoc networks consumed much energy of user devices, which usually becomes critical in disaster areas. Power supply is also a main issue for constructing a mesh network using remaining infrastructure in such an area because power outage might occur. A different approach is using satellites to provide services such as satellite phones. It can be superior to other methods in terms of service coverage and the ability of using in isolated areas. However, due to the cost of the satellite related equipment, the number of users able to use satellite services is, indeed, limited.

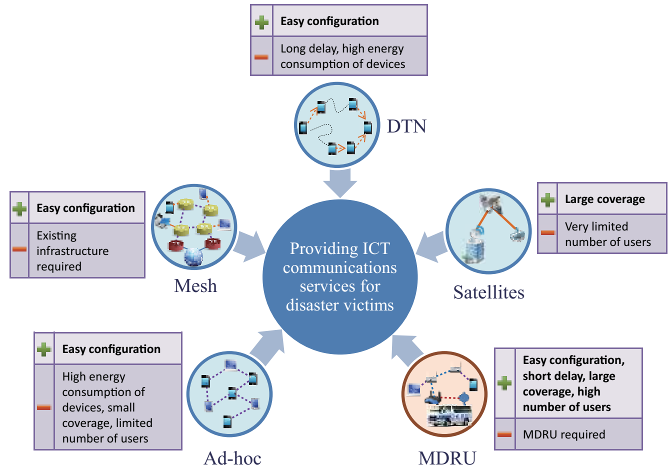
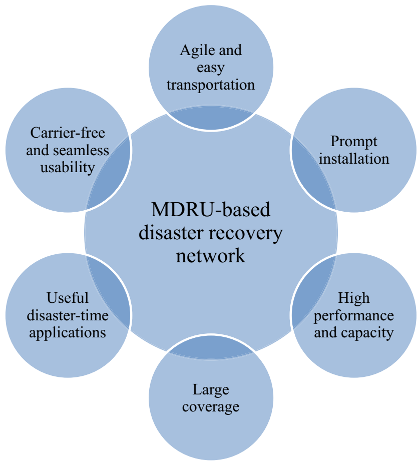


Fig. 1. MDRU is a promising solution for the critical supply-demand problem in disaster areas.

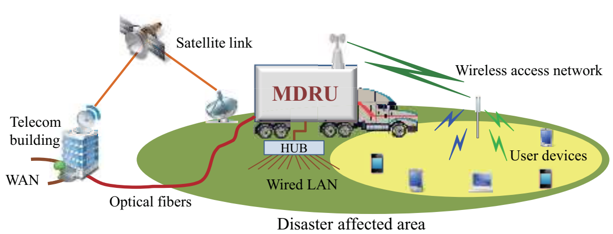
In fact, the users in disaster-stricken areas need all the above-mentioned features. The expected network needs to be easily configured, and provide services to a high number of users while still covering a large area. Those features are expected to be provided by the MDRU, which contains all necessary equipment in a resource unit and is able to configure a recovery network in the disaster area. In the following section, we discuss in detail the required features of MDRU and how they motivated us to implement the current version of MDRU.

IV. Required Features of MDRU

Although MDRU is a promising solution to recover the services in disaster areas, it needs to satisfy at least the most important requirements from user perspective, as shown in Fig. 2(a). The first response is always the most important



(a) Required features of MDRU.



(b) An envisioned MDRU-based disaster recovery network.

Fig. 2. Required features of MDRU and the disaster recovery network.

phase of disaster recovery. Therefore, an agile and easily transportable MDRU is required. Furthermore, once the MDRU arrives at the disaster area, the MDRU-based recovery network has to be installed promptly.

After the MDRU-based network is installed in the area, it is expected to immediately provide services to all people in the area, who are waiting for any method to communicate. The explosively increased demand leads to the need of having a high performance and capacity network. Moreover, due to the difficulty of transportation in disaster area, each MDRU-based network is expected to provide wireless network connectivity and cover a large area so that the service can reach even isolated places.

Once users achieve network connectivity, what they expect to have are the useful disaster-time applications. Typical examples can be voice and message applications, which is the two basic ways to communicate in any situations. Also, the provided applications has to be easy to use and do not require any complicated setup. In case of using personal phones, the services need to be carrier-free so that the users can use network services regardless of which provider they are using.

Keep the motivation of fulfilling the above-mentioned requirements in mind, we have considered an MDRU-based disaster recovery network as shown in Fig. 2(b). After arriving to the disaster-stricken area, the MDRU will promptly establish a wireless access network in the area. The coverage of the wireless network can be extended by using wireless mesh network where each mesh router is equipped with a battery replenished by renewable energy. People staying close to the MDRU can even have wired connection with the MDRU by using the provided switches and hubs. Moreover, the MDRU is equipped with a transmitter to connect to satellite, and hence, can have connection to outside areas or even the Internet. Although the capacity of the local area network (both wired and wireless) provided by MDRU can be considered to be high, the connection to outside areas using satellite usually has limited capacity. However, it is still meaningful to disaster victims because it can provide services in a very early stage. After that, engineers can search for any remaining network connection in the area and connect to the MDRU to improve the performance, and the MDRU is prepared for that. For example, MDRU has an interface to connect to optical fibers [13], which can be robust with some kinds of disasters such as earthquake and tsunami. If we can find any remaining optical connection to outside areas, the performance of MDRU-based network will be significantly improved in terms of Internet connection. Furthermore, any change in the MDRU's connection to outside world will be seamless to users. They do not need to do any further configuration in their devices to use MDRU's services. Since the MDRU-based recovery network can be considered as a self-deployed system which does not require any remaining infrastructure, it can avoid the bad channel conditions in the disaster area. Furthermore, the MDRU is agile and easy to be transported, and thus, the MDRU-based recovery network can be easily deployed. Therefore, the robustness and reliability of the system can be assured.

TABLE I
MAIN SPECIFICATIONS OF THE VAN-TYPE MDRU.

Item	Contents
Base car	Toyota's Hi-Ace (superimposed load: 1 ton)
Power source	- Gasoline electric generator - Lithium-ion battery unit - Electrical power input from outside
Number of racks	2 (19-inch racks)
Servers	- Application servers (e.g., for IP-PBX) - Server for virtual network control - Server for remote operation - Server/storage for hosting/housing
Link to WAN	1 Gbps media converter
Access network	Wi-Fi (2.4GHz/5GHz), Wired (1Gbps/100Mbps Ethernet)
Access network control	920MHz wireless band

V. THE IMPLEMENTED MDRU

In this section, we introduce the latest implemented version of MDRU, which has all required equipment of our envisioned MDRU introduced in [2]. After that, the most typical service provided by MDRU, which is an Internet Protocol (IP) based voice application, is introduced.

A. Van-type MDRU

After many improvement in designing the MDRU, we have implemented a version of MDRU in which all the necessary

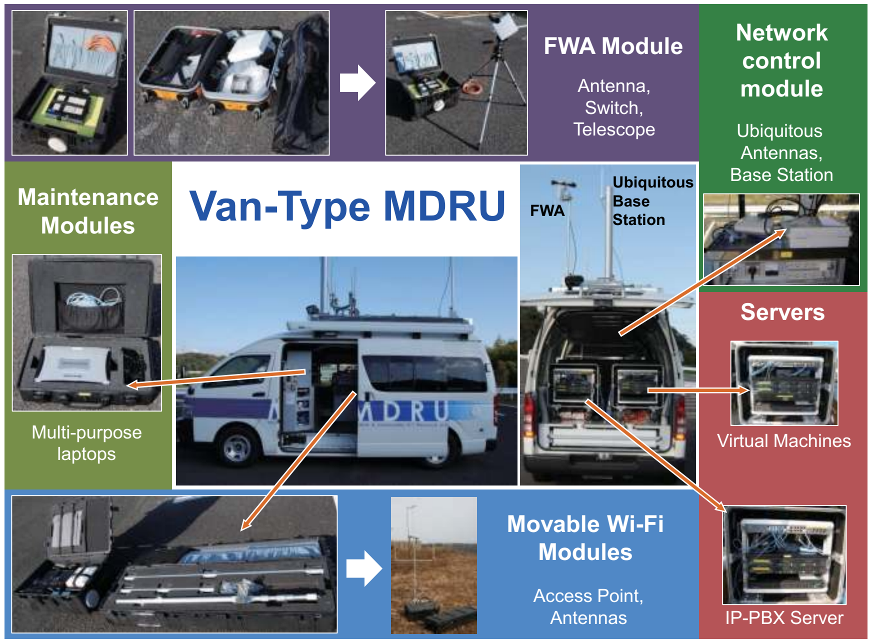


Fig. 3. Modules inside the van-type MDRU.

equipment to construct MDRU-based disaster recovery network is integrated inside a van. Not only servers, storages, and other static equipment but also portable modules utilized to construct a standalone wireless mesh network can be carried by the van. Fig. 3 demonstrates the main modules inside the van-type MDRU and Table I lists its main specifications. A Toyota Hi-Ace with the maximum load of one ton is used as the base vehicular carrying all MDRU's equipment. Servers, storages, and uninterruptible power supply (UPS) are integrated in the basic server module and the extended server module, which are portable but usually kept inside the MDRU to work as a control center. The ubiquitous base station equipped in the network control module is used to control the topology of the mesh network. Four maintenance PC modules, which are multi-purpose laptops, are used to manually manage the system. There are four movable Wi-Fi modules inside the MDRU. Each includes a portable access point (AP) and an antenna set. Each portable AP has a battery replenished by a solar panel. Each antenna set includes two 5GHz, two 2.4GHz, and one 920MHz antennas. 5GHz antennas are used for the connection between APs while 2.4GHz antennas are used for AP-user connections. On the other hand, 920MHz antennas are used to connect to the ubiquitous base station at the MDRU for controlling the network topology. One portable set of fixed wireless access (FWA) equipment is used to make a direct connection with the MDRU from a far distance. When the FWA set is connected with one of the APs in the mesh network, the AP can act as a gateway in the MDRU-based recovery network.

The van-type MDRU can get the power supply from three types of sources, namely gasoline electric generator, lithium-ion battery unit, and electrical power input from outside. Depending on situation, the suitable power source can be chosen. In general, the MDRU can consecutively operate for five days without power supply from outside. One of the factors making the MDRU's operation time longer is that it uses a cooling system based on latent heat storage material. Inside the MDRU, there are two 19-inch racks with servers for applications, virtual network control, remote operation, and hosting. 1 Gbps media converter is used for the link between MDRU and the wide area network (WAN). Beside the wireless access, users can use 1Gbps/100Mbps Ethernet connection if they are close to the MDRU. Since the size of the van-type MDRU is small enough to access many different areas and all the modules are portable, the van-type MDRU is expected to be used in many different situations of disasters.

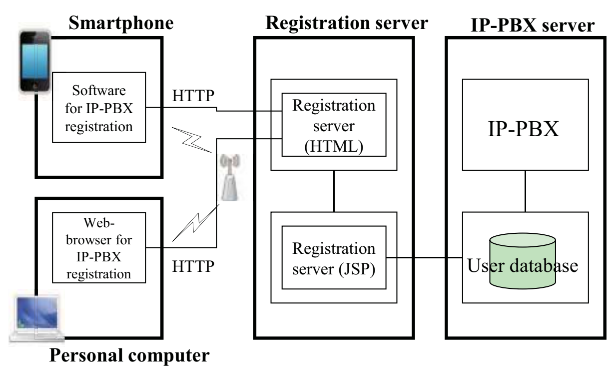


Fig. 4. A typical service provided by MDRU: using voice service to make phone calls not only in damaged area and but also to outside areas.

B. A Typical Service Provided by MDRU

After the occurrence of a disaster, phone call is probably the most useful application for survivors in the disaster area. If they can use phone call, they can ask for help, confirm the safety of others, and tell their relatives and friends that they are safe. Moreover, if the phone call can reach outside

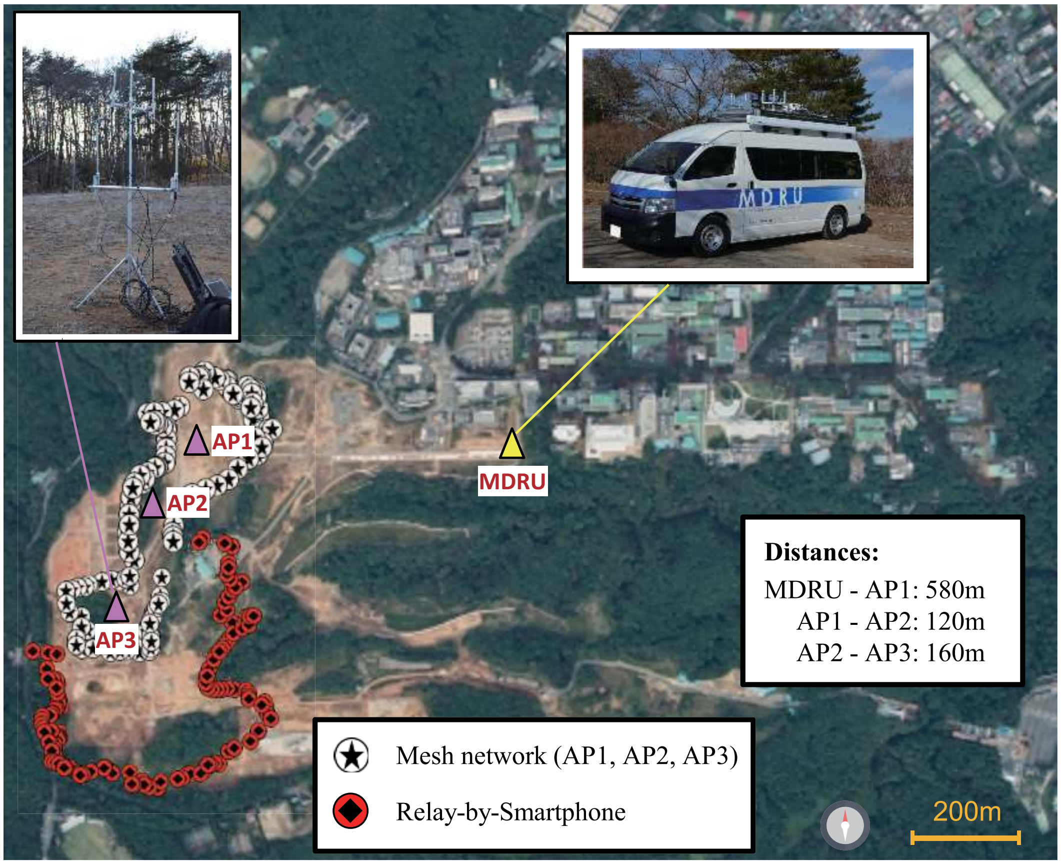


Fig. 5. The extension of coverage area in cases of using wireless network and Relay-by-Smartphone. The experiment was conducted at Tohoku University.

areas, it will significantly help the disaster response. With that motivation, we have implemented the voice service using Internet protocol - private branch exchange (IP-PBX) server. Fig. 4 demonstrates the architecture of the system. Users with smartphones or personal computers (PCs) can use this service when they have connection to the MDRU. With smartphones, users can register for IP-PBX service via the IP-PBX software, which can be downloaded and installed on site by accessing to a server in the MDRU via WiFi. Users do not need to install the software prior to disasters. On the other hand, users using PCs can register for IP-PBX service via web browser. The registration is carried out by using hypertext transfer protocol (HTTP) request to the registration server. The hypertext markup language (HTML) division in the register server is in charge of user interface while the Java server pages (JSP) division takes the role of writing user records to user database located in IP-PBX server. Finally, the IP-PBX server provides the voice service by using the embedded user database. Note that when users register the service, they can use their real phone number as the identity (ID) stored in the database so that everyone can make the phone call as regular calls. With the current settings, the IP-PBX server in an MDRU can accommodate one hundred users simultaneously using the voice service. When the MDRU can have connection to outside areas by using optical fibers and/or satellite communication links, users in the disaster areas can call to any real phone number via the call center located in Yokosuka, Japan. Furthermore, anybody can make regular call to the IP-PBX call center to communicate with people in the disaster area having connection to MDRU.

VI. Field Tests with Van-type MDRU

After implementing the van-type MDRU, we have conducted many field tests including those in Fukushima prefecture and Sendai city to confirm the performance of the MDRU-based recovery network. The successful connection with satellite via WINDS [5] has been also confirmed. For the understanding of the MDRU's performance and the ability to combine with other technologies, in this section, we introduce the coverage of MDRU-based wireless mesh network and its extension by connecting the van-type MDRU to Relay-by-Smartphone. Note that in the scope of this article, we only introduce the field tests with a van-type MDRU. Interested readers can find the discussion on the optimal deployment and the capacity optimization in other works of our research group [14], [15].

A. Coverage of Van-type MDRU Based Wireless Network

As one of the field tests, we have conducted an experiment in Tohoku University, Miyagi prefecture, Japan, to measure how far the coverage area of the MDRU-based recovery network can be extended in the real field. Three portable APs, i.e., AP1, AP2, and AP3 in Fig. 5, were used in this experiment. Each portable access point was equipped with two

5GHz, two 2.4GHz, and one 920MHz antennas, a battery, and a solar panel to replenish the battery. The 5GHz antennas were used for the connection between APs to configure a mesh network between them. The 2.4GHz antennas were used for AP-user connection. The topology of the mesh network constructed by APs was controlled by the MDRU using the 920MHz antennas. In this experiment, a line topology was constructed with the three APs whereby AP1 was connected to the FWA set to have connection with the MDRU placed 580 meters away. Hence, AP1 played the role of the gateway in the constructed mesh network. Smartphones, on which the IP-PBX voice application was installed, were used to make test phone calls. Global positioning system (GPS) loggers were used to record the locations where the smartphones were able to run the voice service. It is worth noting that the terrain of the experiment was mainly mountainous, which is considerably difficult for deploying the mesh network. However, as shown in Fig. 5, AP3 placed approximately 700 meters away from the MDRU can still provide the users with the MDRU's voice service.

B. Extension of Coverage by Connecting Van-type MDRU to Relay-by-Smartphone

In this experiment, we attempted to connect the MDRU-based wireless mesh network with Relay-by-Smartphone system, which utilizes Wi-Fi functionality of smartphones to relay messages between them [4]. Our objective was to measure how far the smartphones can communicate with the MDRU-based mesh network by using the relay function. In other words, we attempted to evaluate how much the service coverage of MDRU-based recovery network can be extended by using Relay-by-Smartphone. The topology of the mesh network was kept the same as the previous experiment. The application used in this experiment was the message service. Seven smartphones having the Relay-by-Smartphone application were used in the south part of AP3 to construct a relay network among the smartphones. The relay network was connected to AP3 and all the smartphones were either 1-hop or 2-hop away from AP3. All the smartphones attempted to send messages to a server directly connected with the MDRU by using Ethernet connection. As demonstrated in Fig. 5, the result shows that the service coverage of AP3 was remarkably extended with 2-hop relay of Relay-by-Smartphone. In fact, the service coverage was measured to be extended by 2.7 times. Although the smartphones in this experiment were connected to only the AP3, it is considered that we can also connect user devices to other APs in MDRU-based wireless mesh network to significantly extend the service coverage of MDRU.

VII. Future of MDRUs

One of the directions that we are pursuing is to make the disaster recovery network based on multiple MDRUs [15]. Although the first sight of this direction seems to be simple, i.e., only extending the coverage area by adding more MDRUs, it covers many research issues that need to be considered for practical implementation. "How many MDRUs are enough for a given disaster area?", "how to deploy and operate the MDRUs in spectrum-efficient and energy-efficient way?", "how to do load balancing between MDRUs?"... are the questions need to be effectively answered. The reasons are the cost of making an MDRU is very high, the spectrum resource in an area is limited while the demand of users suddenly increases, the MDRU needs to use battery or power generator, the capacity of one MDRU is limited, and so forth.

Another direction that we are following is to make even more compact and modularized versions of MDRUs to deal with more variation of disasters. This direction will lead to the research issues not only in hardware design but also the network design to maintain the performance while reduce the size of MDRUs. How to connect the modularized MDRUs in a mesh or ad hoc fashion to fully utilize the capability of the MDRUs also has a good potential.

VIII. Concluding Remarks

In this article, we discussed the most important requirements for disaster response and how the MDRU meets all of them. It motivated us to implement the newest version of MDRU, called van-type MDRU, which can carry all necessary equipment for establishing a disaster recovery network in a van. A number of field tests were conducted to verify the performance of our MDRU-based disaster recovery network and the success of connecting with other technologies such as Relay-by-Smartphone and satellite. The results obtained from the experiments are encouraging, and demonstrate the immense potential of the MDRU-based technology for achieving effective disaster response.

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Satoshi Kotabe received the B.E. and M.E. degrees in electronic engineering from Ibaraki University, Ibaraki, in 1993 and 1995, respectively. He is currently a senior research engineer at the Media Innovation Laboratory, NTT Network Innovation Laboratories. Since joining NTT in 1995, he has been mainly working on high-speed data communication network architectures. His current research includes the protocols and architectures of disaster relief networks. He is a member of IEICE.

Tetsuro Komukai received his B.E. degree in electrical engineering and his M.E. degree in electrical and communication engineering from Tohoku University, Sendai, Japan, in 1986 and 1988, respectively, and his Ph.D. degree in electronics engineering from the University of Tokyo, Tokyo, Japan, in 2004. In 1988, he joined the NTT Transmission Systems Laboratories, Ibaraki, Japan. He is currently a senior research engineer at the NTT Network Innovation Laboratories, Yokosuka, Japan.

Tomoaki Kumagai received his B.E., M.E., and Ph.D. degrees from Tohoku University, Sendai, Japan, in 1990, 1992, and 2008, respectively. He had been a senior research engineer and supervisor in the NTT Network Innovation Laboratories. Since joining NTT in 1992, he has been engaged in research and development of personal communication systems and high-speed Wireless Local Area Network (WLAN) systems. Currently, he is with Advanced Telecommunications Research Institute International (ATR) in Kyoto. He received the Young Engineer Award from IEICE in 1999.

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