Disaster-Resilient Networking: A New Vision Based on Movable and Deployable Resource Units

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Abstract

During the great east Japan earthquake on March 11, 2011, a lot of ICT resources — telecom switching offices, optical fiber links, and so forth — were completely or partially damaged due to the tremor and the resultant tsunami. As a consequence, the demand for ICT services explosively increased, mainly because the people of the affected areas were trying desperately to communicate with the outside world that led to a phenomenal rise in the network traffic. In the Nippon Telegraph and Telephone (NTT) East Corporation alone, 385 telephone offices stopped operating immediately following the earthquake because of power outages and disruption of facilities. Approximately 1.5 million users were cut off from using fixed-line telephone service. The demand for fixed-line and mobile telephone services jumped up to 10–50 times the usual. This gave rise to serious traffic congestion, and the emergency ICT networks and services could not deal with this issue sufficiently. This article proposes a network architecture that is resilient even through devastating disasters by effectively exploiting specially designed movable and deployable resource units, which we refer to as MDRUs. An MDRU having the ability to accommodate communication and information processing functions can be rapidly transported or moved to the disaster zone, and can be deployed within a reasonably short time to establish the network at the disaster site and launch ICT services. The concept and configuration of the network architecture based on the MDRU and its features are described in this article. Some preliminary simulation results are also reported to evaluate the performance of our adopted MDRU-based disaster resilient network.

On March 11, 2011, the great east Japan earthquake and the resultant tsunami hit a wide area of the eastern part of Japan. Most social infrastructures, such as transportation, electric power, gas, water, and telecommunication services, suffered serious damages due to the tremor and tsunami, which isolated the inhabitants of the disaster-affected areas from the rest of the world. The aftermath of the event raised serious concerns that require urgent consideration and resolution, especially in the information and communication technology (ICT) sector. Quite a few ICT resources, such as telecom switching offices, optical fiber links, and base stations for mobile services were either completely lost or partially damaged, which resulted in outage or serious quality degradation of the much required ICT services. At the same time, the demand for ICT services explosively increased just after the event since the people of the affected zones were desperately seeking to communicate with friends and family members both inside and outside of the disaster-stricken areas. The ICT traffic burst was also caused by the urgent need for information acquisition on the damage, and the communications for direction and management in the critical situation among the government, private companies, and other organizations. These situations caused serious traffic congestion in both fixed-line and mobile telephone services. The Nippon Telegraph and Telephone (NTT) group, one of the major telecom carriers in Japan, expended a great deal of effort in order to recover from the damaged network immediately after the earthquake, and it succeeded in restoring its network services in a significantly short period of time (i.e., within approximately a month and a half). However, the restoration time was far from meeting the expectations and requirements of the people living in the affected areas. People recognized the importance of the ICT network as a major social infrastructure that needs to be resilient even under catastrophic disaster scenarios. The realization of a resilient network is therefore recognized as a critical issue that needs urgent resolution.

NTT has long been prepared for such disasters with the

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Item	Damages
Traffic at peak	Approximately 9 times larger than usual
Failed buildings	385
Out-of-service subscriber lines	1.5 million
Time for service restoration	90 days (excluding nuclear power plant area and evacuated area)
Amount of equipment damaged	
Trunk lines	90 routes (excluding power plant area)
Communication buildings	16 collapsed, 12 flooded
Telephone poles	28,000 (coastal area)
Cables on the poles	2700 km (coastal area)

Table 1. *Damages of ICT network infrastructure due to the disaster (NTT East).*

accumulated lessons learned from previous disasters. Installation of container-type temporal switching systems for telephone services is one of the technologies developed by NTT to combat ICT damage in the event of floods. Such systems were applied to replace the flooded switching offices and restore the services in approximately one to two weeks. The handling of traffic congestion was still a major issue to be resolved to retain ICT functionality as a social infrastructure. In order to deal with this and other critical issues for ICT services, the Ministry of Internal Affairs and Communications (MIC) in Japan launched a national project involving industry and academia. Through the collaboration of research teams from NTT, NTT Communications, Tohoku University, and Fujitsu, a disaster-resilient network is proposed in this article that is based on a transportable ICT node, which we refer to as a *movable and deployable resource unit* (MDRU). Our presented work demonstrates the basic technology of the MDRU, and shows how it can be effectively exploited to quickly formulate disaster-resilient networks as part of the national project in Japan. An MDRU accommodates communication equipment, servers and storage, power supply equipment, and air conditioning or other cooling systems. The proposed architecture makes it possible to promptly construct an ICT network in the damaged area by transporting the MDRUs to a disaster-affected area and interconnecting it to network components: customer premises equipment, optical fibers, and so forth. The architecture can be applied to large-scale disaster areas to effectively meet the critical ICT service demands.

The remainder of the article is organized as follows. The related research work is presented. The requirements for a disaster-resilient network are derived. We propose and describe the MDRU architecture as a candidate to meet the requirements. Some preliminary results are provided and discussed. Finally, concluding remarks are presented.

Related Research Work

NTT has been carrying out research to develop measures for preventing communication interruptions caused by natural disasters for a long time [1]. In the work in [1], important lessons learned from previous major disasters (e.g., the Tokachi-oki earthquake in 1968, the Los Angeles earthquake in 1971, the Asahikawa office fire in 1975, the Miyagi prefecture tremor in 1978, Nagasaki Prefecture heavy rains in 1982) were used to outline disaster countermeasures implemented at NTT. The disaster countermeasures included the concept of improvement of network reliability, reinforcement of communication facilities, prevention of communication isolation of cities, towns, and villages, and rapid restoration of communication services. However, the March 2011 earthquake and tsunami in Japan raised new concerns and challenges to promptly formulate disaster-resilient communication networks.

Sugino [2] presented the summary of the damages of the great east Japan earthquake and tsunami in March 2011. The damages to the telecommunication network in terms of service disruption, network traffic congestion, and base station blackouts were discussed in [2]. This revealed that 1.9 million fixed telephone lines and 29,000 cellular base stations had been damaged. According to [2], the emergency restoration took one month, while full restoration took 11 months. The emergency restoration within the first month used rerouting and temporary replacement of damaged equipment in the core network. The work stressed the fact that communication networks must be more resilient both on short-term and long-term bases. In particular, research and development (R&D) on portable communication processing facility based on resource units within a substantially short period (e.g., one hour) was recommended to combat widespread damage to communication infrastructure due to disasters.

Challenging Requirements for a Disaster-Resilient Network

Table 1 demonstrates the information of ICT network infrastructure damages due to the devastating earthquake and tsunami in Japan in 2011 that were reported by NTT East. Just after the event, people attempted to use their mobile phones and/or other ICT devices for safety confirmation of their family, friends, assets, and so forth. Companies and local/national governments also rushed to use ICT services to gather information on the damages and victims in the disaster area, and to retain the command and control channel. Therefore, the demand for telephone service and other ICT services significantly spiked. In the case of fixed-line telephone service, the demand was nine times higher than usual. At the same time, the number of subscriber lines that were out of service reached 1.5 million just after the event. Furthermore, telecom carriers restricted the performance of switching systems to avoid system crashes caused by the traffic congestion. These statistics suggest that the potential demand for telephone and other ICT services should be much higher than the reported one, especially in disaster areas. Three hundred eighty-five communication buildings failed, and other equipment such as trunk lines, telephone poles, and cables on the poles suffered serious damage. NTT mobilized 6500 personnel to restore the services. Thanks to their hard work, it took only about 50 days to almost restore the services and the network, including the 385 communication buildings that had failed and other equipment. It was a surprisingly short period of time given the scale of the catastrophic damage. However, a much shorter restoration time is required to fulfill the service demand and the social expectation of ICT services, which explosively increased after the event.

In order to come up with the solution for this issue, we pro-

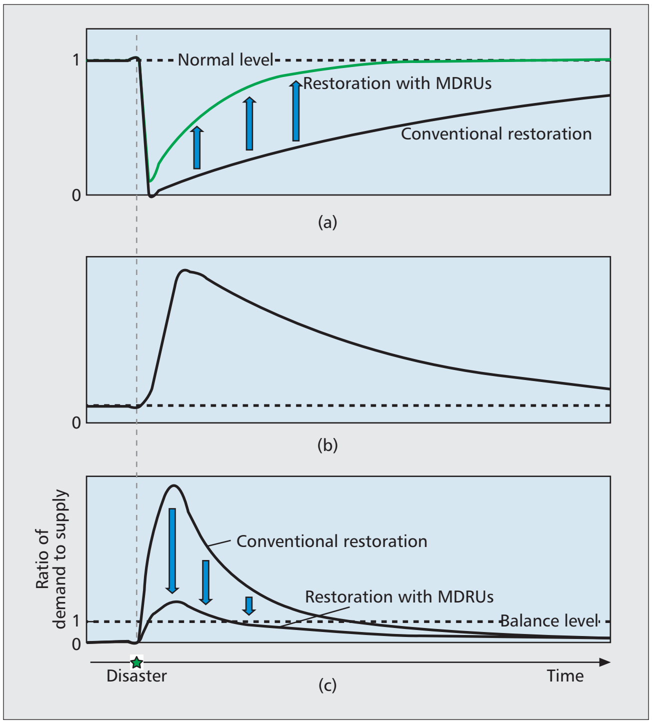

Figure 1. *Concept of how to compensate the reduced capacity due to the disaster by deploying MDRUs: a) service supply; b) service demand; c) demand/supply.*

pose a network architecture based on a transportable ICT node, the above mentioned MDRU. The MDRU is a transportable container that accommodates modularized equipment for networking, information processing, and storage. Once a disaster occurs, MDRUs are transported to the damaged area. The interconnections between the MDRUs and the backbone networks can quickly establish network access and provide ICT services. The network architecture based on MDRUs enables us to promptly restore the network in a damaged area and provide the ICT services that are urgently required in a disaster situation.

Figure 1 demonstrates the concept of how to compensate for the reduced capacity due to a disaster by deploying MDRUs. The figure consists of three graphs:

- ICT service and/or resource supply trend after a large-scale disaster
- Trend of ICT service demand after the disaster
- Trend of the gap between the supply and the demand, which is defined by the ratio of the demand to the supply

As shown in the figure, once a devastating disaster occurs, ICT service and/or resource supply goes down to a very low level due to the damages of ICT resources, the outage of electric power, and other reasons. The supply level then goes up gradually because of the restoration effort of people in the ICT sector. After the earthquake, NTT along with other telecom carriers experienced an explosive increase of ICT service demand. People sought to use ICT services for safety confirmation of family, relatives, friends, and their assets. Moreover, the government, private companies, and other entities attempted to use ICT service for their management. Therefore, the demand in and around the damaged area remarkably increased. Figure 1c expresses the ratio of ICT service demand to supply. If the ratio is equal to one, the supply and demand are at the same level. In this case, the ICT resource usage efficiency becomes 100 percent. On the other hand, if the ratio is greater than one, the demand will surpass the supply, and traffic congestion will occur. In our proposed architecture, the ICT resource accommodated in an MDRU is brought to the disaster area immediately after the disaster and accelerates the restoration speed. This urgent installation of ICT resources to the damaged area helps to keep the demand/supply ratio around or below one, and thus alleviates the critical situation caused by traffic congestion.

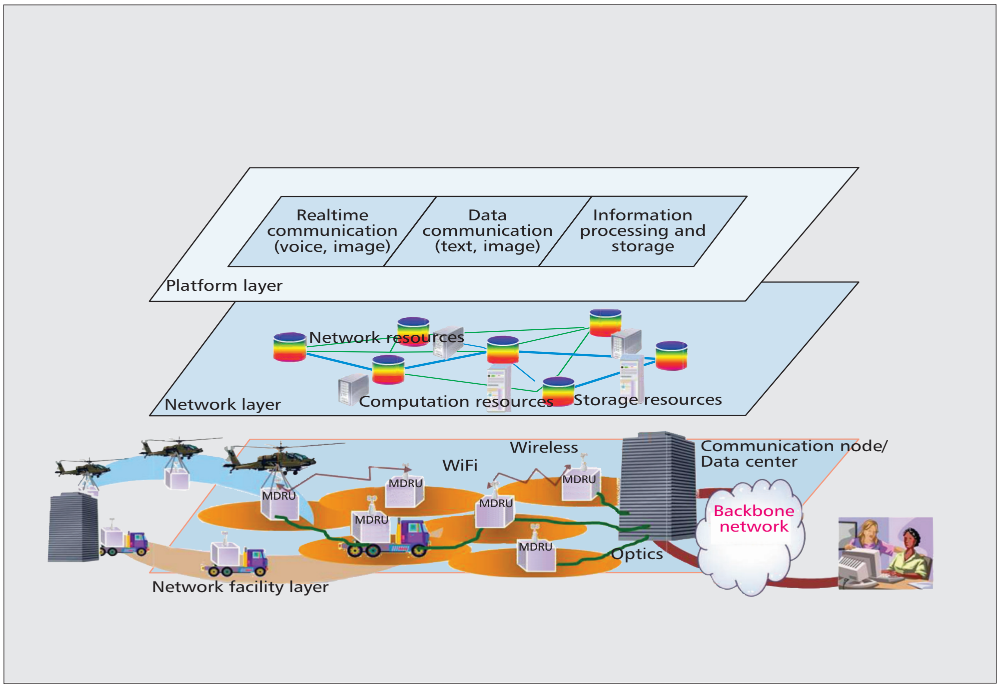

Figure 2. *Considered system overview.*

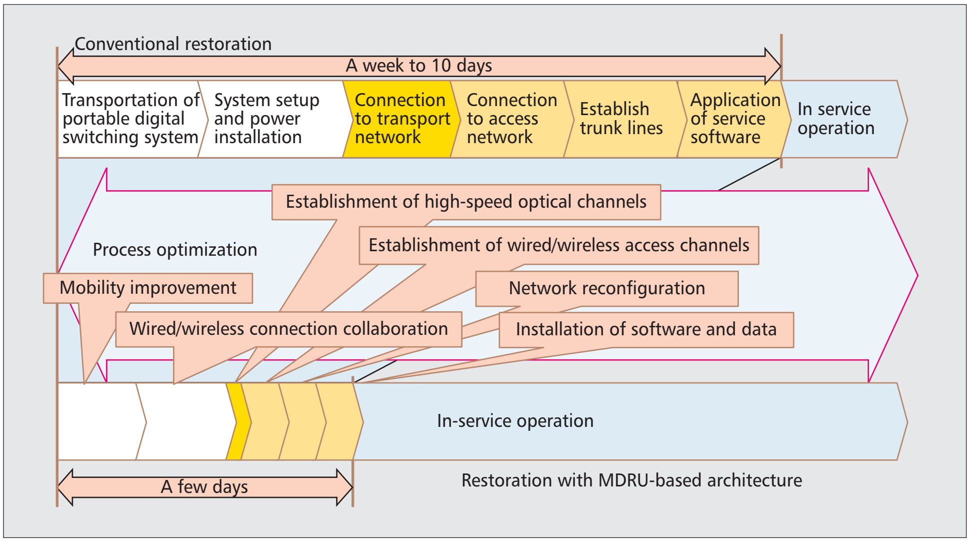

Figure 3. *The objective of the MDRU architecture.*

Envisioned Architecture Based on MDRUs

In this section, we provide an overview of the architecture based on MDRUs, the process of network restoration using our proposed scheme in contrast with conventional restoration techniques [3–6], and the specifications of an MDRU. Figure 2 depicts the system overview of the MDRU-based architecture. It comprises three layers: network facility, network, and platform layers. Thus, each MDRU comprises modular functionalities, which are required in disaster-resilient networks [7, 8]. In the network facility layer, MDRUs can be transported by helicopters, vehicles, or any other means to the disaster area. Each MDRU is a container or box, which accommodates equipment for ICT services such as switches/routers, wired/wireless transmitters/receivers, servers, storage devices, power distribution units, and air conditioners. Once an MDRU is deployed to the disaster area, electrical power is fed to it from available power sources such as available power lines, on-premises generators, batteries, and power supply vehicles. Thus, the MDRU forms a wireless access network around it to reach customer premises equipment. Wired access through Ethernet cables is also available near the evacuation sites. One of the lessons learned from the great east Japan earthquake is that optical fiber cables installed underground are robust to earthquakes and tsunamis. After the great disaster, most optical fibers under the ground were not damaged even in the tsunami affected areas. The MDRU uses such "surviving" optical fibers to retain bandwidth to the metro core and nationwide networks. Wired and/or wireless interconnections, which are chosen depending on the situation, form the MDRU network to retain the service coverage in the disaster area. The network layer consists of switches, routers, servers, storage devices, and other ICT equipment to offer networking and information processing/storage functions. Virtualized technologies for network and processing can be applied to efficiently utilize the physical resources. The platform layer offers various applications for ICT services that are demanded in the disaster area. The most commonly demanded applications after disasters are supported. They include real-time communication, data communication, and information processing/storage services. The MDRU network is installed in the disaster area where it is usually difficult to assign engineers for installation, operation, and maintenance. The ability to monitor the status of the network and control it remotely is indispensable for making the network resilient. Therefore, the MDRU network has remote operation and maintenance functions so as to minimize the number of engineers and workloads.

One of the key advantages of the network architecture is the speed of installing the network and launching ICT services in the disaster area [9]. Figure 3 shows the objective of the MDRU-based network architecture and the process from the occurrence of a disaster to the availability of services in the damaged area. The upper and lower flows express the processes of restoration based on a conventional transportable switching system and restoration based on the proposed architecture, respectively. In the conventional restoration technique, the process starts at the time of disaster occurrence, as shown in the upper flow in the figure. The first step is to transport the portable switching system to the disaster area. After that, the system is set up and electric power is installed. The next step is to establish connections to the transport and access networks. After the physical line establishment, trunk lines are set up to make the connections to customer premises equipment. Applications and data are installed for the equipment in the system, and then services are provided to users. With conventional restoration using a portable switching system, it usually takes a week to 10 days from the event to start providing services. This time span is still far from the expectation of people in and around the disaster area. Therefore, the proposed network architecture based on MDRUs attempts to reduce the restoration period to a few days. This shortening of service delivery time must contribute to making not only the network resilient, but also the services on the network meet the demand in critical situations. The proposed architecture has many features that shorten the service delivery time. MDRUs have portability, which enables us to use a wide variety of transportation forms: helicopters, trucks, ships, and so forth. It is secure, since the functions inside each MDRU are modularized and virtualized. The collaboration of wired and wireless interconnections makes the installation of the network flexible. The application of high-speed optical transmission technology, which is based on digital coherent technology using the unscathed underground optical fibers, is promising to rapidly establish the interconnections between the backbone network and MDRUs in a cost-effective way. Since a large amount of bandwidth (e.g., over 40 Gb/s) is available only by splicing one or a pair of optical fiber(s), the time and cost for these interconnections become quite small. Once the MDRUs are set up in the disaster area, they create network access. Wireless technologies like WiFi and fixed wireless access (FWA) are applied to the network. Network configura-

Key features

Set up time: within two days since the disaster occurrence
Service coverage: 500m in radius per MDRU
Accomodation: 5,000 users (extendable to 30,000 by adding MDRUs)

Applications

VoIP, mail, internet access, and other information services

Network/processing/storage

Network: wired and/or wireless depending on the situation
Backbone-MDRU: 100Gbps optical channels
Inter-MDRU: fixed wireless access or 100Gbps optical channels
Access to users: mainly single-hop/multi-hop wireless WiFi (2.4/5GHz) mesh and ad-hoc networks with the combination of quasi-millimeter wave band fixed wireless access system

Processing: stacked blade servers

Storage: solid state drive (SSD), hard disk drive (HDD)

Facilities

Container dimension: W9.0m x D2.4m x H2.7m
Power supply: 200V three-phase A.C. (no limit) / battery (30min.) / power supply car (days as long as refuel continues)
Cooling facility: air conditioner

Figure 4. *The specifications of a typical MDRU.*

tion and software/data installation for the services are also performed. These steps are arranged optimally to make the overall duration from the disaster occurrence to the timing of providing services to be within a few days. NTT Corp., Tohoku University, NTT Communications Corp., and Fujitsu Corp. launched a collaborative R&D project to establish fundamental technologies of the proposed architecture under a national project supported by MIC of Japan.

Figure 4 summarizes the typical specifications of an MDRU that we aim to use in the project. The first prototype of the MDRU is under development and is scheduled to be deployed at Tohoku University for field trial by March 2013. A system using multiple helicopter-portable MDRUs is also under design. The prototype is scheduled to be completed by 2015, supported by MIC. The key features of our initially envisioned MDRU are as follows. It can configure the network within a few days, has a service coverage of 500 m in radius, and can provide a network for 5000 users. These features work effectively to realize the concept described in the previous section.

In summary, the features of our proposed system comprise the following features:

- The concept of movable and quickly deployable resource units referred to as MDRUs
- Facilitating MDRU deployment in an easily handled fashion
- Utilizing a quasi-millimeter-wave band FWA system or surviving optical fiber as the backhaul network
- Cooperation among MDRUs to cover affected areas dynamically
- Establish hybrid networks comprising mesh and ad hoc networks

Note that each of the above features has been designed for the MDRU to be more scalable to cater to the needs of a significantly high number of users in a disaster area. In contrast with conventional portable switches or network equipment, an MDRU offers a large-scale moving platform with real-time communication, information processing and storage, and so forth (as shown in Fig. 2) to facilitate disaster-resilient communication.

Preliminary Results

In this section, the preliminary results of the proposed MDRU-based approach are presented for evaluation. The simulation is constructed using Qualnet 5.1. We base the simulation on the case study in Tagajo, which has the densest population in the Miyagi Prefecture of Japan and was seriously affected by the March 11 earthquake and tsunami in 2011. The city has an estimated population of 61,621 (updated on June 30, 2012) and a total area of 19.65 km^2. The considered scenario is shown in Fig. 5a. As mentioned in the previous section, each MDRU has a service coverage of 500 m in radius. We divide the coverage area of the MDRU into seven hexagonal cells. Each cell has a gateway at its center. Since the MDRU connects to all the gateways inside its coverage via a quasi-millimeter-wave band FWA system, we consider that there is no bottleneck in the connections between the gateways and the MDRU. Therefore, in order to evaluate the throughput of the network, we evaluate the throughput at each gateway. In other words, the network inside one cell is simulated.

In the conducted simulation, each cell has 18 access points (APs) connecting to the center gateway via an 802.11a 5GHz channel. These links have a physical data rate of 18 Mb/s. One channel is used for AP-gateway links. Based on the density of Tagajo, each cell has approximately 400 users on average. However, as each MDRU is designed to accommodate 5000 users (i.e., each cell has approximately 720 users), the number of users is varied from 1 to 720 in our conducted simulation. These users connect to the APs via 802.11g 2.4 GHz. The physical data rate of user-AP links are set to 48 Mb/s. To simulate the worst case scenario, the number of channels is set to one. We assume that all users simultaneously send data to the gateway with the same load. The data packet size is set to 1200 bytes, which corresponds with the maximum transmission unit size of a typical wireless network. A free space path loss model is considered, and the 802.11 request to send/clear to send (RTS/CTS) mechanism is used in the simulation.

After running the simulation with different values of load per user, we obtained the results shown in Fig. 5b. The results are the average values calculated after running 25 different simulation scenarios. The confidence level of these results is 95 percent. As demonstrated in this figure, the aggregate throughput at the gateway is bounded by the theoretical maximum throughput (i.e., 12.18 Mb/s for data packet size of 1200 bytes and data rate of 18 Mb/s [10]). As a result, although the aggregate throughput can keep the upper bound value when the number of users is considerably high, the throughput per user decreases. In fact, when the number of users is significantly higher, the network throughput decreases with regard

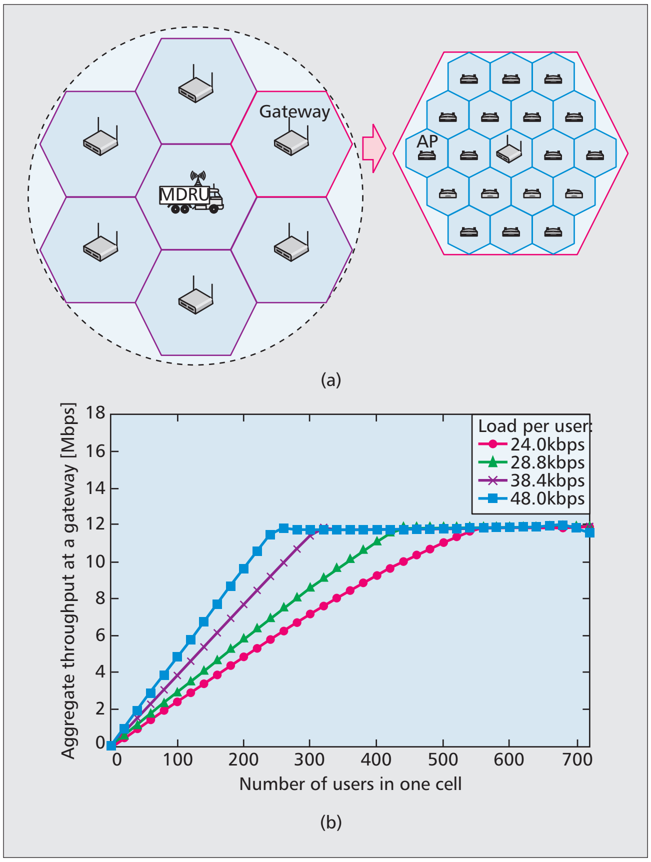

Figure 5. *Preliminary results based on the case study in Tagajo: a) considered scenario with seven hexagonal cells in the coverage of one MDRU; b) throughput at a gateway with different loads from users.*

to the number of users. However, with the maximum 720 users/cell, the aggregate throughput at the gateway still remains approximately 12 Mb/s.

When the load from each user does not exceed 28.8 kb/s, 440 users/cell can send packets to the gateways at the same time without any packet loss. In other words, with the population density in Tagajo, all the users are able to simultaneously access the Internet with the load up to 28.8 kb/s. In some places with relatively lower population density, each user can send packets with even higher traffic loads. On the other hand, in comparatively higher population density areas, the network can still provide Internet access but with lower shared load for users (e.g., 24.0 kb/s for 560 users). Thus, the results in this simulation indicate that if we design the recovery network as mentioned in the considered scenario, each cell in the MDRU-covered network is able to effectively provide connectivity to a significantly high number of users.

Conclusion

This article proposes a disaster-resilient network architecture based on movable and deployable resource units. The lesson learned from the great east Japan earthquake is that alleviating the gap between the demand and supply of ICT services, which causes serious traffic congestion after disasters, is a critical issue that needs to be solved. The proposed MDRU-based architecture is a promising candidate to solve this problem. In this article, we describe the system architecture, the specifications of an MDRU, the concept of how the system solves the problem, and the restoration process using MDRUs. We also introduce some preliminary results achieved using simulation based on a case study in Tagajo in northeast Japan. The simulation results demonstrated that each cell in the MDRU-covered network successfully provides connectivity to a reasonably high number of users.

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Biographies

Toshikazu Sakano received his B.E., M.E., and Ph.D. degrees in electronics engineering from Tohoku University, Sendai, Japan, in 1985, 1987, and 1998, respectively. In 1987, he joined NTT Laboratories, Yokosuka, Japan, and is now a senior research engineer and supervisor there. Since joining NTT Labs, he has been active in several research and development fields including optical signal processing for high-performance computer systems, super-high-definition (SHD) imaging systems, photonic network architectures, and large-capacity optical transmission systems. He received the Young Engineer Award from the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan in 1995.

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