Chapter 2

# Multi-Tier Networks for Citywide Damage Monitoring in a Natural Disaster

Takahiro Fujiwara and Takashi Watanabe

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/55513

## 1. Introduction

Progress of computer networks and mobile communications are leading to the environments capable of accessing networks anytime, anywhere. Furthermore, ubiquitous networks which are emerging in a smart city would awaken expectations to acquire any information with a hotspot panel in a whole city [1]. People expect to acquire information through the Internet with mobile devices or information appliances as usual, even in case of a large scale natural disaster. They also expect to contact with family and friends by mobile phones anytime. Though quick, accurate damage informationhas beenstrongly required for speedy and effective rescue operation, those communication systems did not work sufficientlyinthe previous large-scale disasters, due to both damage on facilitiesand communications congestion by heavy use or network overload [2, 3]. As a result, response efforts were delayed, causing further damage that could have been prevented with better communications.

To solve the issue on collecting damage information and personal safety information in a natural disaster, several studieshave been carried out,for example, to provide emergency services in Internet [4] and to maintain communications in evacuation shelters [5]. The Journal of IEICE introduced policy for acquiring damage information and maintaining communications in a disaster [6]. Moreover, regarding recovery from disaster damage in networks, telecommunication service companies have endeavored to mitigate aftermath of a disaster effectively [7]. However, in case of the Great East Japan Earthquake in 2011, telecommunication systems and networks could not maintained services after all [8, 9]. As a result, authorities could not comprehend the damage situations quickly, due to not only the scale of disaster-affected area but also to the loss of lines of communications [10].

This paper firstly reviews some networking technologies for disaster communications, and discusses a scheme on multi-tier damage monitoring in a citywide area. Then, an experimental system configured with a centralized hierarchical network, which was developed to acquire damage information from lifeline facilities installed in residences is shown. Finally, some results of computer simulation for multi-tier networks enhanced with an *ad hoc* networking technique are also presented.

## 2. Technologies for disaster communications

This section reviews some technologies that should be effective for disaster communications to acquire damage information in a large-scale natural or manmade disaster, including related studies on disaster communications.

### 2.1. A concept on damage monitoring in micro and micro perspectives

A concept of an integrated damage monitoring and assessment system was proposed [3], referred to as macro and micro perspectives (Fig. 1). The macro perspective performs comprehensive damage detection using image processing technique with satellite or aerial image. In addition, damage estimation in the aftermath of a disaster should be included in the perspective. The micro perspective, on the other hand, gathers individual damage information from a local site using several sensing devices, receiving emergency calls from suffers, and sharing information about rescue operations. Thus, the damage monitoring system needs to handle several types of information based on macro and micro perspectives. Multi-tier networks described in this paper play a critical role for the micro perspective.

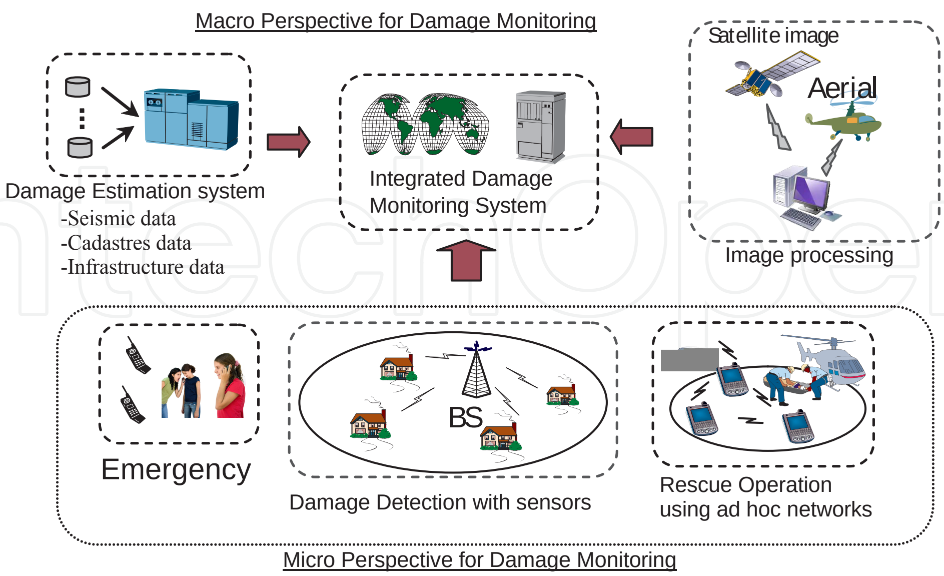


**Figure 1.** A concept of damage monitoring and assessment in a large-scale natural disaster based on macro and micro perspectives

### 2.2. Cellular networks in a disaster

The third-generation (3G) mobile systemshave provided the performance of up to 2 Mbps and various services in application systems [11]. Furthermore, current LTE (Long Term Evolution) and LTE-Advanced systems are providing a broadband mobile communications, leading to the fourth-generation (4G) cellular system, whichshould operate at the data rate of 100 Mbps or more [12, 13]. Since the latest mobile networks are challenging to provide a high data rate and a high capacity, those systems are required to operate at a higher carrier frequency and a large peak transmission power. A concept of virtual cellular system has been studiedand achieved to reduce the average transmission power compared with conventional cellular systems[14]. Thus, the current mobile systems have been developed focusing on high data rate and high capacity, under the policy of the best effort performance in ordinary conditions. However, in a disaster, it is strongly required for the communication systems to ensure connectivity even if difficult.

In the past,immediately after a large-scale natural disaster, massive access to communications systems occurred, and the systems lapsed into communications congestion, in the worst cases resulting in system failure. To both mitigate the congestion and prevent system failure, accessibilityingeneral channels for citizensis restricted into 1/n(Fig. 2). Since the regulation is mainly applied to the telephone call, data communications such as e-mail services might be maintained, even if taking a long delivery time. Meanwhile, prioritized channels have been set up in advance, to maintain connection in a disaster, but the number of the channels is not enough to transmit information from a large-scale damaged areas.

Multi-hopping is one solution to extend and maintain the coverage. A technical report of 3GPP (Third Generation Partnership Project) showeda scheme called ODMA (Opportunity Driven Multiple Access) to maintain high data rate in the edges of the coverage by relaying communications (Fig.3)[15]. Mobile stations located in the high data-rate can access the Base Station (BS) directly. On the other hand, stations outside of the high data-rate cannot maintain the rate. They request a terminal located in the high data-rate area to relay their packets.

Similar idea was proposed, referred to as MRAC (Multi-hop Radio Access Cellular), which aims high speed, high capacity and wide area coverage by multi-hopping [16]. In the system, dedicated Repeater Stations (RS) are set up in a good propagation area, and the stations relay packets between user terminals and BS. In the event that a mobile station detects high propagation loss in the single-hop conditions to BS, the station selects a neighboring RS to relay packets. Hereby, MRAC is capable of expanding the coverage. However, since MRAC premisesmulti-hoping via RS, the restriction of the arrangement of RS reduces flexibility of the system operation. One solution is *ad hoc* networking, to build a network flexibly.

### 2.3. Ad hoc networks

Ad hoc network is a scheme to flexibly build a network without infrastructure facilities [17]. The networkis expected to maintain communications and to collect information even in a disaster. Figure 4 shows a model ofad hoc networks, where terminals are deployed and connected each other flexibly with wireless communications. For example, in rescue opera-

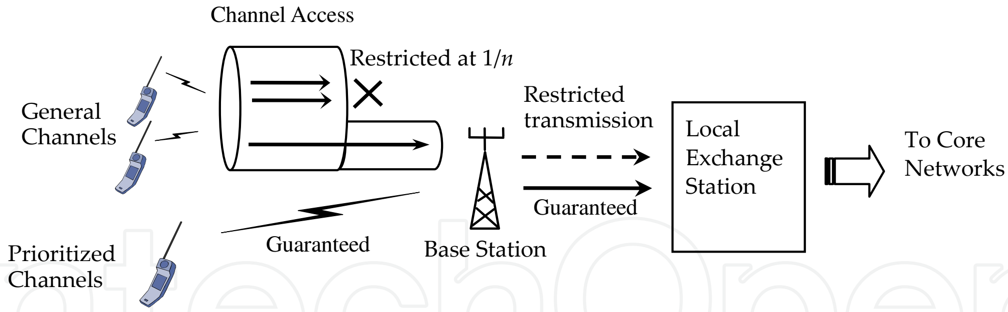


**Figure 2.** Traffic controlby reducing accessibility into 1/n in a disaster.

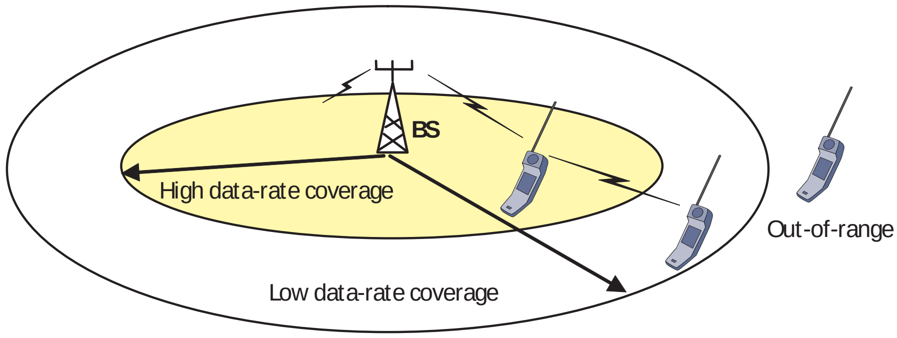


**Figure 3.** Opportunity Driven Multiple Access (ODMA).

tions, the rescue team should work, sharing damage information among the team in the afflicted site.Ad hoc networking technique enables the team to access each other and to share information without infrastructures. The information could be forwarded to an emergency operation center through the mobile base station.

Several protocols to build ad hoc networks flexibly and autonomously have been proposed based on the scheme ofon-demand driven routing protocols such as AODV (Adhoc On-demand Distance Vector routing protocol) [18] and DSR (Dynamic Source Routing protocol) [19], and proactive table-driven routing protocols such as DSDV (Destination Sequence Distance Vector routing protocol)[20] and OLSR (Optimized Link State Routing protocol) [21]. The network scheme may achieve flexible network. However, stable communications environment could not be provided immediately after a large-scale disaster, even in ad hoc networks. In addition, since the links of ad hoc networks are vulnerable, massive control packets such as either route request or route maintenance packets may be induced, resulting in heavy traffic congestion and communications failure.

### 2.4. Hybrid wireless networks

Hybrid wireless networking schemes combiningcellularand multi-hopping technique have been developedto aim high data rate, high capacity, wide area coverage and QoS control, not for disaster communications. The hybrid network named Sphinx [22] aims to achieve high throughput and low power consumption. Concurrently, it addresses fairness for resource allocation, and resilience for mobility. The mobile stations operate in two modes, one is a cellular mode, and the other is a peer-to-peer mode(Fig. 5). When a mobile station communicates with the others located in the same cell, all flows are served in the peer-to-peer mode in the initial state. In the event that a mobile station detects degradation of the throughput in the peer-to-peer mode, it requires BS to switch to the cellular mode.

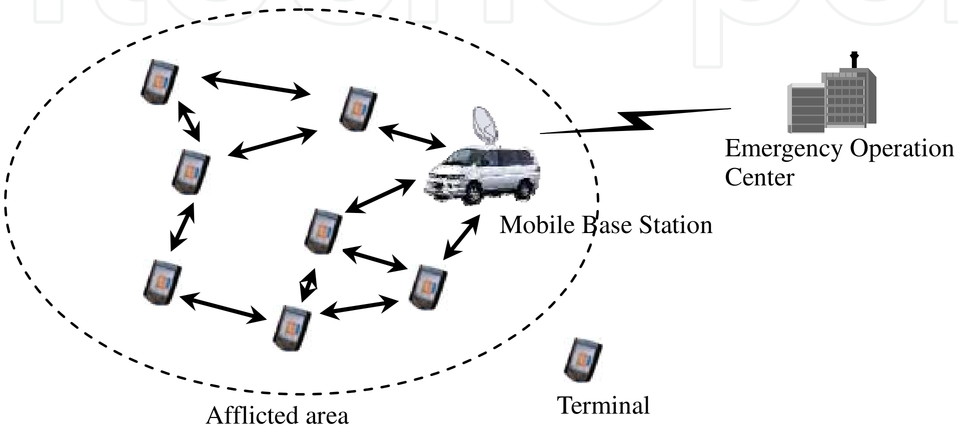


**Figure 4.** A concept of *ad hoc* networks forrescue operations.

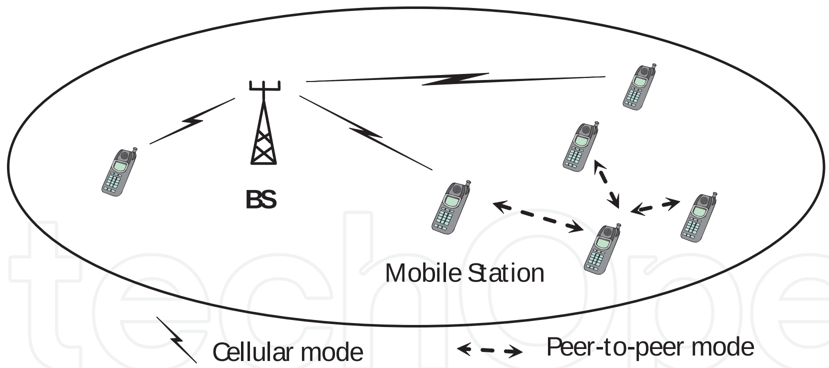


**Figure 5.** Hybrid network model for cellular packet data network (Sphinx).

Another scheme, named iCAR (Integrated Cellular and Ad hoc Relaying System), aims to avoid blocking and dropping communications due to localized congestion, and focuses on traffic load balancing [23]. The system installs ad hoc relay stations (ARS), which are placed at strategic locations to divert traffic in one (possibly congested) cell to another (non-congested) cell (Fig. 6). Terminals in a congested cell try to access a BS of a surrounding non-congested cell via an ARS. Those schemes are focusing on maintaining throughput and other features in ordinary conditions, and such hybrid networks might be effective even in extraordinary conditions, if the system could be resilient to maintain communications.

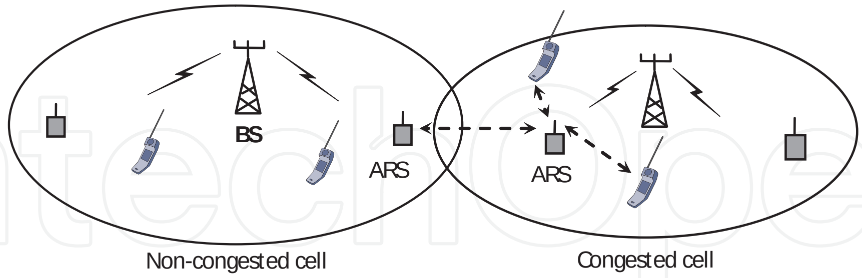


**Figure 6.** Integrated cellular and ad hoc relay system (iCAR).

### 2.5. Wireless sensor networks

Wireless sensor networks premise that massive sensor nodes are deployed in the field and build a network autonomously.The networks transmit data from sensors to a sink node by multi-hopping,which are expected to collect information in several application systems such as environmental monitoring, structural health monitoring and so on. Since the nodes are usually restricted in CPU power and are operating by batteries, it is strongly required to reduce energy consumption [24]. Though several protocols have been proposed, they do not sufficiently consider how to operate in the seismic monitoring.

Assumingseismic monitoring, multiple sensor nodes are placed in buildings, bridges, or structures to detect seismic motion, temperature, or distortion of the structures. Furthermore, the system might be expected to find persons who trapped in the building.The reference [25] describes a seismic acceleration observed in the University of California, Irvine, where the acceleration includes the bandwidth of around 30Hz on the ground and 5Hz on the fourth floor. Thereby, the monitoring system is operating at the sampling rate of 200Hz. Health monitoring of the Golden Gate Bridge was carried out with wireless sensor networks [26]. They achieved the monitoring of the vibration on the bridge by multi-hopping of 46 hops at a sampling rate of 1 KHz. Then, issues to be taken into account in monitoring system are to provide a long time operation and to extend the coverage of damage monitoring in a large-scale disaster.

As an example, Figure 7 shows an outline of the monitoring with a wireless sensor network in a building. The sensor network iscomposedof a number of sensor nodes (SNs), some relay nodes (RNs)and a sink node (SI) to gather data from SNs to SI. The network installs SI and RNs atstrategically designated positionsin advance on one hand. The SNs, on the other hand, are flexibly distributed in the building, and transmit data to RNs directly or via adjacent SNs by way of multi-hopping. The RN relays data to SI using a direct path or a multi-hopping path via RNs. Though, the SI is capable of collecting and storing the data, we have to study how to collect the information from a great number of sink nodes in a whole city.

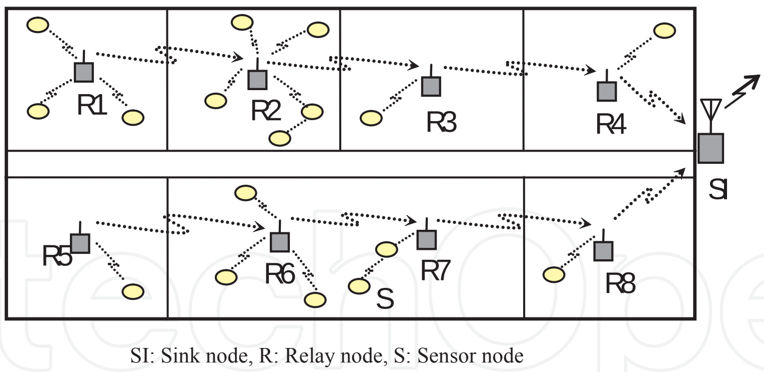


**Figure 7.** Wireless sensor networks deployed in a building

## 3. Multi-tier networks for damage monitoring

Now, we discuss the network design of multi-tier networks to operate for damage monitoring. The architecture of the multi-tier networks is based on the hybrid network, which is configured with a centralized hierarchical network and *ad hoc* networks. In addition, to detect phenomena, wireless sensor networks are introduced and work with the hybrid network for damage monitoring.

In case of large-scale natural disaster, information required for damage assessment changes as time goes by.The authorities need to comprehend the circumstances of damage based on multidirectional aspects. They acquire damage information comprehensively,make a strategy for emergency response, and carry out rescue operation quickly. Though the concept of both the macro and micro perspectives shown in the previous section is nontrivial, we focus on a network model based on the micro perspective to comprehend the conditions of individual damages in an afflicted site.

Figure 8 shows a network model todetect extraordinary phenomenaand to collect the information.The sensors are placed in houses, buildings and structures in a whole city. Information detected by sensors is transmitted to a CS through a base station in the centralized network. The centralized network combines *ad hoc* networking operation to enhance the connectivity, referred to as a hybrid network. The emergency operation center accesses the information stored in the CS through the backbone network such as the Internet.

### 3.1. Damage detection with sensors

Damage detection in a disaster is performed with several sensors; seismic vibration is measured with accelerometers installed in a structure. Meanwhile, wireless sensor networks (WSN) draw attention to detect several phenomena, temperature, humidity, brightness etc. in low cost. As the nodes of WSN contain accelerometers, the networks are capable of detecting seismic acceleration to assess the damage. In addition, lifeline facilities such as gas meters,

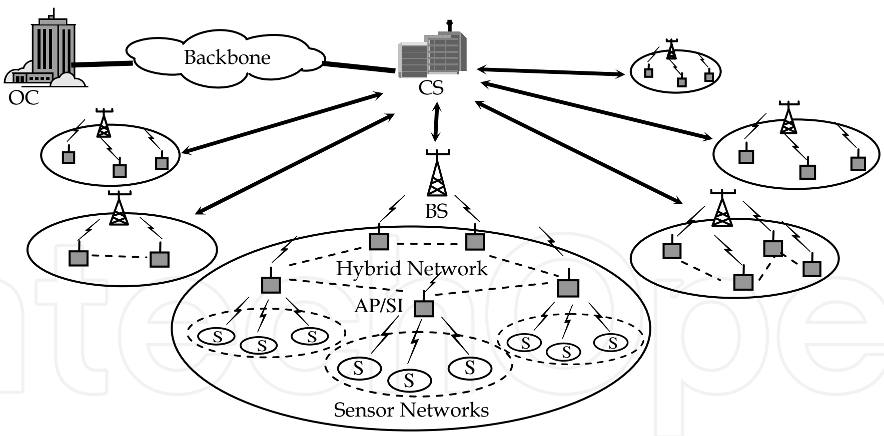


**Figure 8.** Network model for multi-tier damage monitoring in a natural disaster.

electricity meters and water meters include various kinds of sensors to detect conditions of facilities.

Since the communications range of a link in sensor networks is short, e.g., 20 m normally, or 100 m at most, multi-hopping technique is used to expand the coverage. Furthermore, each sensor node operates with a small battery, and the CPU power is restricted to control the operation including the calculation of a routing path. Provided that the scale of the network becomes larger, traffic to relay packets increases and induces large power consumption.

### 3.2. Centralized hierarchical network for damage monitoring

A centralized hierarchical network is composed of multiple terminals and a base station in a cell, and those BS access a CS to transmit the information gathered from terminals (Fig. 9). In ordinary conditions,the network is effective in transmitting packets quickly. If the network is available for quick accurate damage monitoring even in extraordinary conditions, the model would be employed in the monitoring system. However, such network has suffered from disconnection between terminals and BS, and lapsed into communications congestion in a previous large-scale disaster. In collecting damage information and emergency messages from terminals placed in a whole city, it is strongly required to transmit packets efficiently from distributed massive terminals to BS, and from BS to CS for swift rescue operations.

The network model is configured with two layers:the upper layer, composed of a CS and multiple BS connected by either wireless or wired channels, and the lower network,that contains a great number of terminals. Assuming that those terminals are placed in all residences and the collected information is restricted to emergency communications, the volume of the traffic in a cell is almost predictable, and we can design the channel capacity of the network. One concern is, however, those channels are vulnerable in a natural disaster. Especially, cables of wired networks may easily suffer damage. Thereby we should design

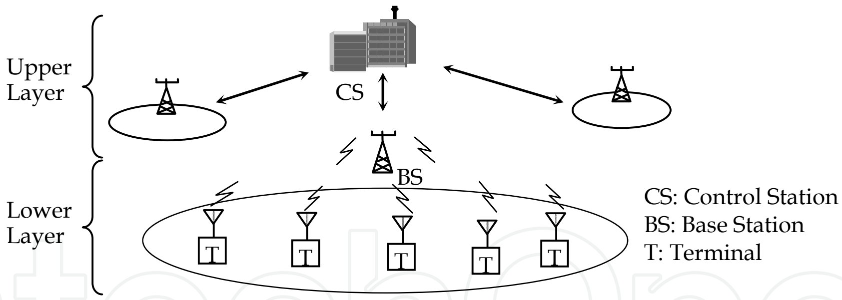


**Figure 9.** Centralized hierarchical network model.

the network to collect damage information quickly considering how to maintain connections in disaster circumstances.

The lower layer network, consists of the BS and multiple terminals in each cell, where the BS and terminals communicate in TD-CDMA (Time Division and Code Division Multiple Access) mode at 2.4 GHz, which is designed based on CDMA (Code Division Multiple Access) and TDMA (Time Division Multiple Access). The output power is 10 mW or less for the communications range of 300 m.

| | Upperlayer | Lowerlayer |
|---|---|---|
| Frequency | 2.1099GHz(Fw)<br>2.2899GHz(Rv) | 2.402GHz(Fw)<br>2.482GHz(Rv) |
| Bandwidth | <200kHz | <1.5MHz |
| Outputpower | 1W | 10mW |
| Modulation | π/4-shiftQPSK | DBPSK(Fw),DQPSK(Rv) |
| Accesscontrol | Polling | TD-CDMA |
| Datarate | 288kbps | 19.2kbps(Fw)<br>9.6kbps(Rv) |

**Table 1.** Air interface parameters of channels in the upper and lower layers (Fw: Forward-link; Rw: Reverse-link)

| | Forward-link | Reverse-link |
|---|---|---|
| Chiprate | 1.2288Mcps | 1.2288Mcps |
| Datasize | 156B | 256B |
| Framelength | 320ms | 320ms |
| Datarate | 19.2ksps | 9.6ksps |
| Processinggain | 64 | 128 |

**Table 2.** Data transmission parameters of the CDMA channels.

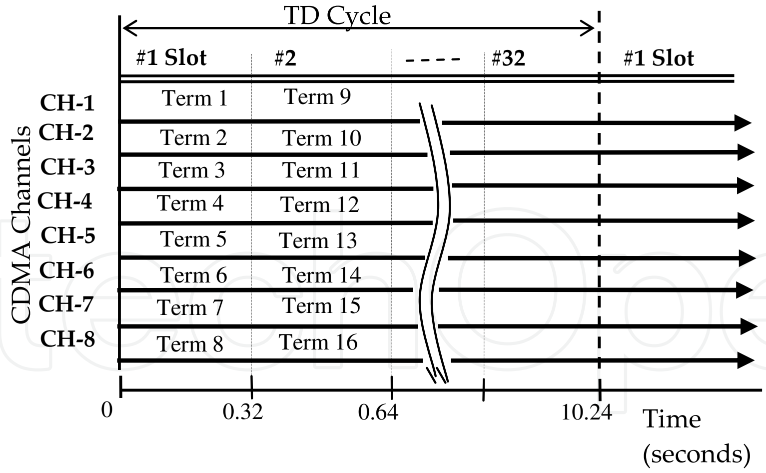


**Figure 10.** Channel operation in TD-CDMA

The experimental system was designed to contain 256 terminals in a cell. The communications system of the radio channels connecting terminals with BS in the lower layer employs CDMA technology operating at 2.4GHz. The communications system also introducesthe time division mode,hence, referred to as TD-CDMA. Figure 10shows the time chart ofthe TD-CDMA operation. The multiplexed CDMA channels are divided into 32 timeslots of 320ms, to operate in the time-division-multiple-access mode. A group of 8 terminals, e.g. terminals 1 through 8, is assigned to one timeslot. 8 terminals are invoked at the timing of the #1 slot, and transmit data to the BS via CDMA channels. Thus, the BS is capable of collecting data from 256 (8´32) terminals in one TD-cycle of 10.24 seconds. The parameters of CDMAchannelsand data transmission are shown in Table 1 and 2.

### 3.3. Hybrid wireless monitoring enhanced with *ad hoc* networks

A centralized network showsa good performance for damage monitoring in conditions where the links between a base station and terminals are maintained. *Ad hoc* networking, on the other hand, allows a node to rebuild a route by alternative links even if the connection of the links may not be maintained. However, the links of *ad hoc* networks are vulnerabledue to not only mobility or limited power but also interferences or deteriorated propagation conditions. Thereby, ahybrid wireless network combining *adhoc*networks and a centralized network has drawn attention for disaster communications [27].

The hybridnetwork(Fig. 11) combines both schemes of the centralized hierarchical network (CH mode) connecting BS and nodes directly, and the *ad hoc* networks (AD mode) connecting nodes each other. If the condition ofthe link between BS and a node is getting worse and the connection cannot maintain, the node shifts the operation to the *ad hoc* mode and accesses a neighboring node, where the node relay packets to BS.

In normal conditions, most of nodes access BS directly in Cellular mode. Ifa disaster occurs and several links between BS andnodesare disconnected due todamage or obstacles, those nodes switch to *ad hoc* mode, and attempt to build a route to BS by way of multi-hopping.

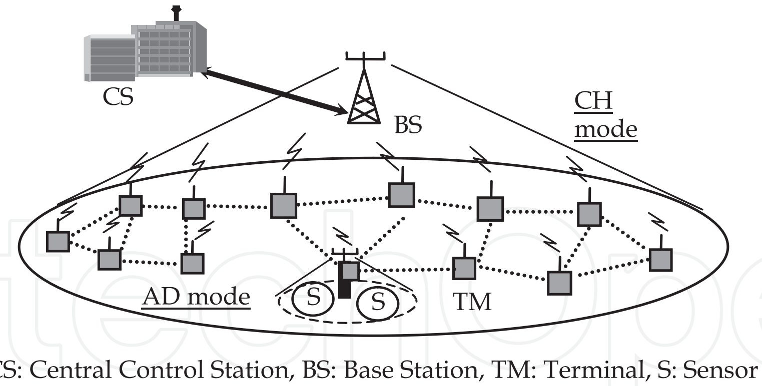


**Figure 11.** Hybrid wireless network enhanced with *ad hoc* networks.

Provided that the node discovers a node which can access BS directly or other nodes which already found a route to BS, the node requests one of the neighboring nodes to forward damage data to BS.

To build a connection in AD mode of the hybrid network, each node, which cannot access BS directly, needs to discover a route to reach BS. Every node operating in either cellular or *ad hoc*mode (CH or AD mode) periodically transmits a control packet. The control packet includes the number of hops (Hop-CNT) to reach BS, the addresses of source, destination, sender and receiver nodes (Fig.12).

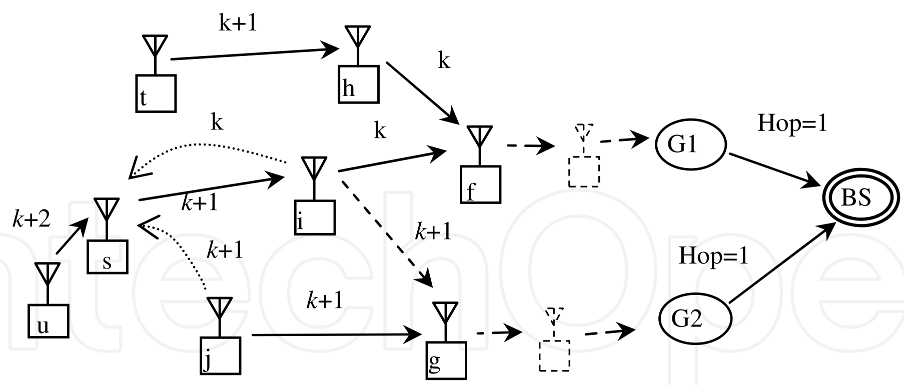


**Figure 12.** A scenario in route discovery.

Inthe route discovery, a node (node-s), which cannot access BS, monitors communication of neighboring nodes. Overhearing a packet, the node checks Hop-CNT of the received packet, and knows how many hops are required to reach BS. It selects a node (node-i) as the next hop node based on the received Hop-CNT. The node-s records the address and the Hop-CNT of node-I; receiving a packet from node-s, the node-i forwards the packet since it already knows a route to reach the BS in a multi-hoping.

Provided that node-s detects multiple nodes which can reach BS, it records the nodes' address and Hop-CNT, and selects a node which has the shortest hopping range. If multiple nodes are found whichhave the shortest route, it may select one of them randomly. Provided that node-s notices it cannot overhear the communicationsfromthe node recorded in its routing table during the time to live (TTL), node-s decides the node is not available and deletes the record of the node in the table. The value of TTL is designated as a system parameter in advance.

Provided that a certain node transmits a packet, its Hop-CNT is set up at the value incrementing the value of the next hop node. Thereby, the further neighboring nodes can overhear the communications and discover an available next hop node. Node-i is transmitting a packet to node-f at Hop-CNT=k. node-j is also transmitting at k+1. node-s overhears from node-i and -j at Hop-CNT=k and k+1, respectively. Then, node-s selects node-i, and transmits a packet to the node at Hop-CNT=k+1. Likewise, node-u discovers a route via node-s. Thus, nodes discover a route by overhearing neighbor communications, and establish a route via the neighboring nodes.

When an intermediate node (node-f) is required to relay a packet by a node (node-i), it forwards the packet to the next hop node according to the routing table. Concurrently, node-f records in its routing table the addresses of node-i and the source node (node-s) for the backward path. When a reply packet arrives at node-f to deliver to node-s, node-f recognizes to relay the packet to node-i according to the routing table. Likewise, node-i relays the packet to node-s.

In the event that an intermediate node (node-i) detects failure in forwarding a packet to the next hop node (node-f ), node-i replies an error message to the backward node (node-s) according to the routing table, then deletes the data of node-f from the routing table of node-i. In conditions where node-i does not have another next hop node information in the table, it returns expiration as the error message to node-s. If node-i has an alternative path in the routing table, it returns route-error instead of expiration to its backward node. When the route-error arrives at the source node, the node retransmits the packet to the same next hop node as alternative path. Then, node-i forwards the packet to the alternative node, node-g. When the source node receives expiration, it must select another next hop node. If there is no entry in the table of the source node, the source node has to hold on until it detects a new entry node by overhearing.

## 4. Experimental system

### 4.1. Experimental centralized hierarchical network

A dedicated data collection system was developed based on centralized hierarchical networking scheme for damage monitoring. The experimental system was designed tocollect datafrom lifeline facilities such as gas pipelines, water pipelines and sensing devices [28, 29]. The systemwas configured with two layers, to monitor the state of city lifelines of about 256,000 residences in a whole city.

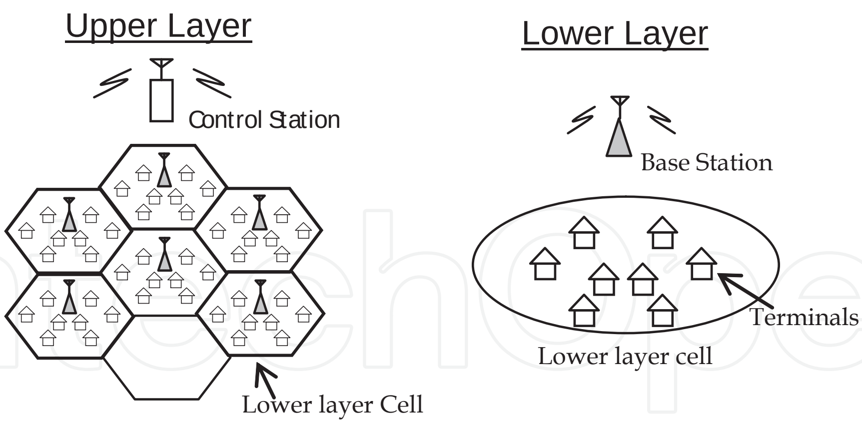


**Figure 13.** A model of acentralized hierarchical damage monitoring system.

The experimental system comprises two-tier networks to cover a total of 250k terminals in an urban area of about 260 km$^2$(Fig. 13). The system employs 2.1 GHz radio communications for the upper layer and 2.4GHz CDMA forthe lower layer, and gathers data from gas meters, water meters and extra signals installed in houses to comprehend the conditions of lifeline facilities.

The upper layer network was designed to covers a whole citywith1024 cells.The central control station accesses the BS of each cell with a TDM (Time Division Multiplexing) wireless system. The upper layer radio system employed a narrow-band radio communications of 2.1GHz to connect CS and multiple BS, where the output power is 1 W, to cover a long distance. The air interface parameters are listed in Table 1. CS and BS of the upper layer contain a database server (Fig. 14):data transmitted from terminals to BS are stored in the database, and the server of BS provides data according to the requirement of CS. The CS stores the data in the database and provides the data in an application system.

The lower layer network consists of BS and multiple terminals in a cell, where the BS and terminals communicate in TD-CDMA at 2.4 GHz, combining CDMA and TDMA technologies. The output power is 10 mW or less in the communications range of 300 m. Though the experimental system was designed to contain 256 terminals in a cell, 128 terminals were actually installed in a residential area. The interface unit contained ina terminal is connected to a liquefied petroleum gas (LPG) meter, natural gas (NG) meter, water meter and additional signals (Fig. 14). Figure 15 shows the experimental CDMA and interface units connecting with meters.

Frame error rate (FER) is defined as the rate of communications failure in two-way transmission. The experiment observed and recorded the number of communications failure in each of 128 terminals, as in Figure 16, where the FER is indicated on the average of 128 terminals. The average FER was approximately 1.5×10−3. Thereby, the experiment showed the CDMA system achieved a low FER on the order of 10−3 even in the output power of 10mW, where the communications range is within 300m.

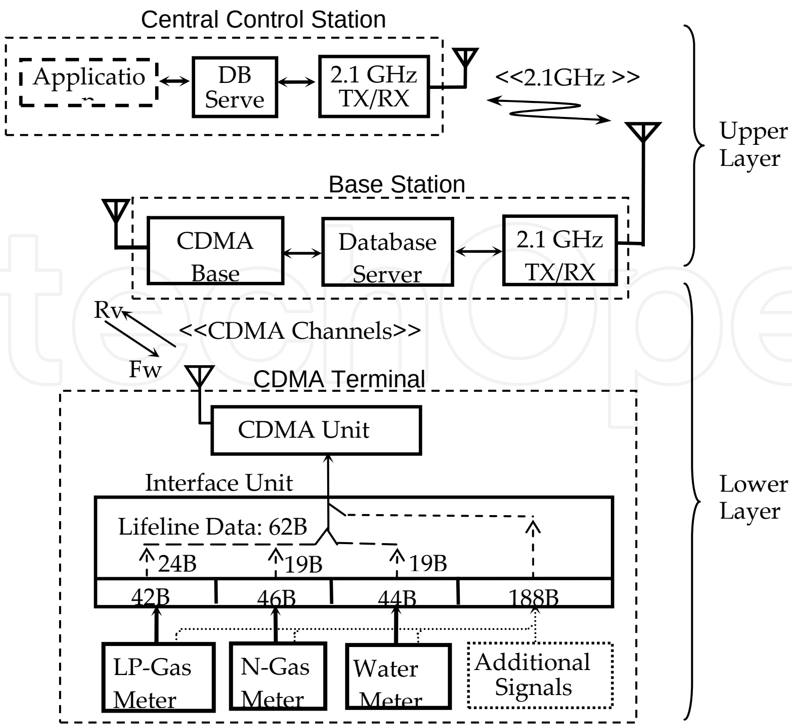


**Figure 14.** Experimental system for lifeline monitoring.

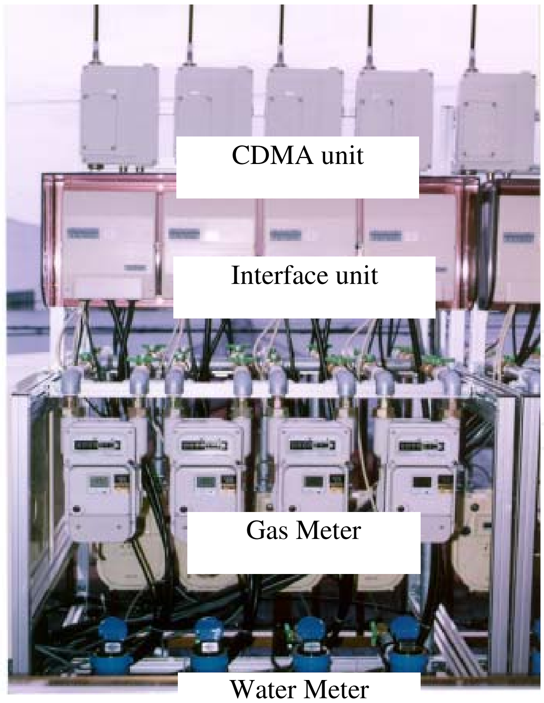


**Figure 15.** Experimental units.

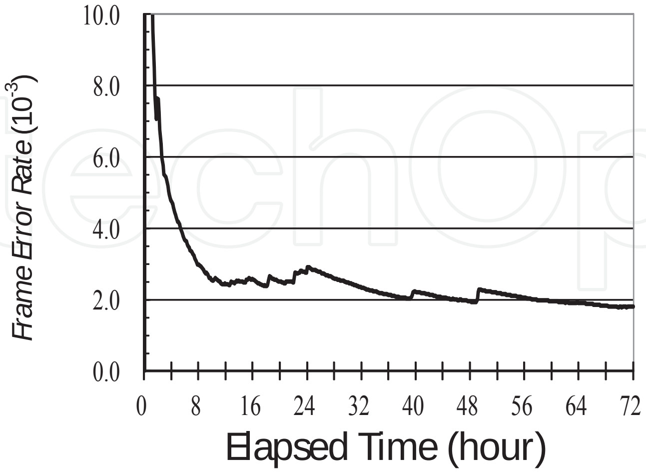


**Figure 16.** Time series behaviour of FER in CDMA channels.

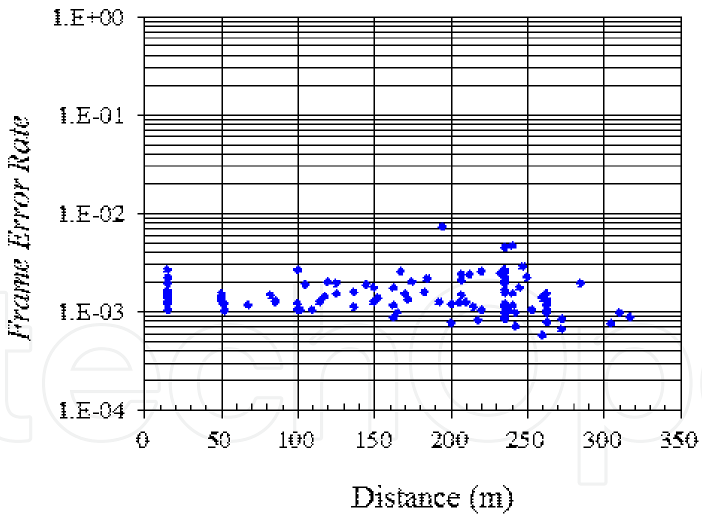


**Figure 17.** *FER*of each terminal

The experimental CDMA system in the lower layer was designed to access 256 terminals in the interval of 10.24 seconds. The experiments confirmed that the system operates in 10.24sec-ondsfor256 terminals (128 actual terminals and 128 dummy terminals). On the other hand, the data rate in the upper layer was designed to transmit data at 288 kbit/s from BS to CS in the polling mode. The experiments showed the data collection time from 1024 BS (three BS and 1021 dummy stations) to CS was 424 seconds in conditions where the data size from each BS is 5120 bytes, i.e. 20 bytes times 256 terminals. To acquire urgent information from every terminal immediately, the BS extracts the state information of two bytes from the data which was acquired in each terminal, and gathers the urgent data of 512 bytes in the cell. By transmitting 512-byte data to CS, the data collection time from 1024 BS was 51.7 seconds.

Thus, the system can collect a small data of two bytes from 256,000 terminals within 60 seconds though it takes about 7 minutes to collect a large size of data of 20 bytes from 256,000 terminals. Thereby, multi-tier centralized network is able tosurvey damage to lifeline in a whole city within one minute.

### 4.2. Hybrid wireless monitoring enhanced with *ad hoc* networks

The hybrid wireless network enhanced with *ad hoc* networks described in the previous section was evaluated by computer simulation, assuming a round shapecell the radius of which is denoted by r. BS is placed at the middle of the cell, and nodes are arranged in grid in a cell, where the grid interval is denoted by d.

Nodes for CH mode are selected randomly according to DCNR, which is defined later. Those nodes work as gateway nodes to relay packets from nodes. The rest of nodes operate in AD mode.

Assume that the communications range (l) of a node operating in AD mode is equal to the grid interval (d). Each node can access four adjacent nodes. This assumption is based on installing nodes in a residential area, which is arranged in grid. Assuming the distance between houses is 20m, the grid interval is 20m, and the communications range is also 20m.

Direct Connection Node Ratio (DCNR) is defined as the ratio of nodes, which can access BS directly, and is given by equation (1).

$$DCNR = \frac{\text{Number of direct connection nodes}}{\text{Total number of nodes in a cell}} = \frac{m_1}{N} \tag{1}$$

where m1 is the number of nodes which can reach BS at one hop, and N is the number of all nodes in a cell.

Reachability ($\gamma$) is defined as the ratio of the nodes that are able to reach BS directly or by multi-hopping. The maximum hopping range (MR) is the upper limit of multi-hopping count (n). Reachability within n hops ($\gamma$ (n)) is given by equation (2).

$$\gamma(n) = \sum_{i=1}^{n} m_i \Big/ N = \gamma_1 + \gamma_3 + \cdots + \gamma_n \tag{2}$$

where $m_i$ is the number of nodes reachable to BS at i hops, and $\gamma_1$, $\gamma_2$,, $\gamma_n$ are the reachability in each hop count from one to n.

Average of throughput within n hops ($\overline{\eta(n)}$) is the ratio of the number of transmitted packets during T (seconds) to the amount of packets that all nodes can transmit in the network, and is given by equation (3).

$$\overline{\eta(n)} = \sum_{i=1}^{n} q_i(T) \Big/ N \cdot T \tag{3}$$

where $q_i(T)$ is the number of packets arriving at BS by i hops during T seconds.

Results are shown in Figure 18, in conditions where the radius of the cell is 340m, and the number of nodes is 901. In conditions where DCNR is 60% or higher, reachability at MR=2 is up to 98%. Even if DCNR is only 20%, it maintains reachability of approximately 90% within three hops. Figure 19 shows the throughput as a function of DCNR, in conditions where the cell size is 340m. Even if increasing MR at 1, 2, 3 and unlimited hopping, throughput is not improved drastically like reachability.

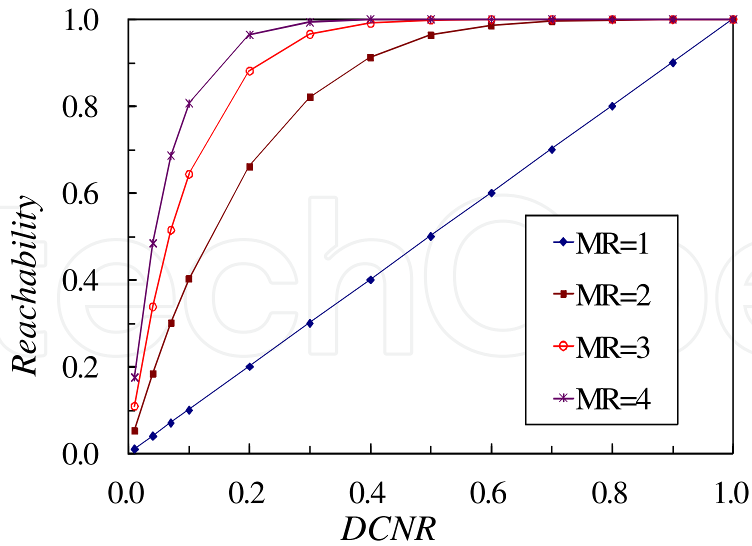


**Figure 18.** Reachability for DCNR.

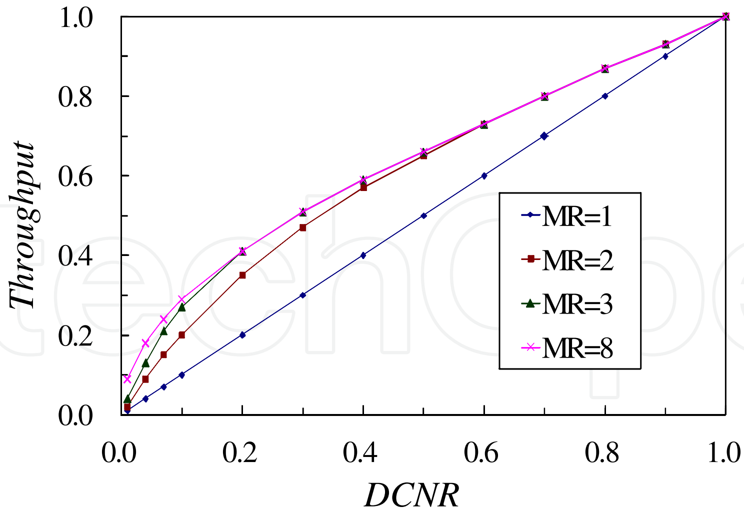


**Figure 19.** Throughput for DCNR.

## 5. Conclusion

We discussed a scheme of multi-tier networks for citywide damage monitoring in a natural disaster. We showed the scheme of the centralized hierarchical network and the experimental system designed for dedicated damage monitoring. The results showed the experimental TD-CDMA system achieved the frame error rate on the order of 10−3 even in the output power of 10mW, where the communications range is within 300m. The monitoring system is capable of collecting information within one minute from 256,000 terminals deployed in a whole city. Thereby, the system is useful and effective to collect data quickly and stably in conditions where the links could be maintained. Based on the concept of the centralized hierarchical network and the experimental results, we showed the hybrid wireless monitoring system enhanced with *ad hoc* networks. The experiments by computer simulation showed the network is capable of improving reachability of packets even in the damage conditions in a natural disaster.

## Author details

Takahiro Fujiwara[1] and Takashi Watanabe[2]

1 Department of Computer Engineering, Hakodate National College of Technology, Hakodate, Japan

2 Graduate School of Science and Technology, Shizuoka University, Hamamatsu, Japan

http://dx.doi.org/10.5772/55513

## References

[1] Gil-Castineira F, Costa-Montenegro E, Gonzalez-Castano FJ, Lopez-Bravo C,OjalaT, Bose R,(2011). Experiences inside the Ubiquitous Oulu Smart City, IEEE Computer Magazine, Vol. 44, No. 6, pp. 48-55.

[2] Balachandran K, Budka KC, Chu TP, Doumi TL, and Kang JH, (2006). Mobile Responder Communication Networks for Public Safety, IEEE Communications Magazine, Vol. 44, No. 1, pp. 56-64.

[3] Fujiwara T, Watanabe T, (2008). A Scheme for Damage Information Gathering Based on Micro Perspective in Sensor Networks, Proc. of IEEE 22nd International Conference on Advanced Information Networking and Applications (AINA2008), pp. 1095-1100, Okinawa.

[4] Schulzrinne H, Arabshian K, (2002). Providing Emergency Services in Internet Telephony, IEEE Internet Computing, Vol. 6, No. 3, pp. 39-47.

[5] Mase K, Okada H, Azuma N, (2010). Development of an Emergency Communication System for Evacuees of Shelters, Proc. of IEEE Wireless Communications and Networking Conference (WCNC 2010), pp. 1-6, Sydney.

[6] Nakazawa J, Takahashi K, (2006). Policy and Planning for Ensuring Information and Communication Networks/Services in Disasters, The Journal of IEICE, vol. 89, no. 9, pp. 782-786 (In Japanese).

[7] Morrison KT, (2011). Rapidly Recovering from the Catastrophic Loss of a Major Telecommunications Office, IEEE Communications Magazine, Vol. 49, No. 1, pp. 28-35.

[8] Yamaji E, (2012). The Disaster Recovery and Challenges of the Telecom Infrastructure, The Journal of IEICE, vol. 95, no. 3, pp. 195-200 (In Japanese).

[9] Takayama S, Kaname T, Akioka M, Takahashi T, (2012). Disaster Area Support on the Great East Japan Earthquake by Communication Satellite WINDS and ETS-VIII, The Journal of IEICE, vol. 95, no. 3, pp. 201-206 (In Japanese).

[10] Ministry of Internal Affairs and Communications (MIC), Japan, Impact of the Great East Japan Earthquake on telecommunications and broadcasting services and associated response, MIC Communications News, Vol. 22, No. 04, May 16, 2011, http://www.soumu.go.jp/main_sosiki/joho_tsusin/eng/Releases/NewsLetter/Vol22/vol22_04/vol22_04.pdf.

[11] Omori S, Yamao Y, Nakajima N, (2000). The Future Generations of Mobile Communications Based on Broadband Access Technologies, IEEE Communications Magazine, vol.38, no.12, pp.134-142.

[12] Baker M, (2012). From LTE-Advances to the Future, IEEE Communications Magazine, Vol. 50, No. 2, pp. 116-71120.

[13] Tao X, Xu X, and Cui Q, (2012)An Overview of Cooperative Communications, IEEE Communications Magazine, Vol. 50, No. 6, pp. 65-71.

[14] Kudoh E, Adachi F, (2002). Transmit power and Frequency Efficiencies of Virtual Cellular Mobile Network, Technical Report of IEICE, vol.102, RCS2002-323, pp. 99-6104.

[15] 3GPP TSG-RAN, Opportunity Driven Multiple Access, 3GPP Technical Report, 3G TR 25.924, v1.0.0, December 1999.

[16] Yamao Y, Otsu T, Fujiwara A, Hidekazu, Murata, Yoshida S, (2002) Multi-hop Radio Access Cellular Concept for Fourth-Generation Mobile Communications System, Proc. of IEEE PIMRC2002, Lisbon.

[17] Royer EM, Toh CK, (1999). (A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks, IEEE Personal Communications, vol.6, No.2, pp.46-55.

[18] Perkins CE andRoyer EM, (1999). Ad-hoc On-Demand Distance Vector Routing, Proceeding of the 2nd IEEE Workshop on Mobile Computing System and Applications, pp.90-100, New Orleans.

[19] Johnson DB, Maltz DA, (1996). Dynamic Source Routing in Ad Hoc wireless Networks, Mobile Computing, T. Imielinski and H. Korth, Eds., pp.153-181, Kluwer Academic.

[20] Perkins CE, Bhagwat P, (1994). Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers, Proceedings of the ACM SIGCOMM'94, pp.234-244, London.

[21] Jacquet P, Muhlethaler P, Clausen P, Laouiti A, Qayyum A, Viennot L, (2001). Optimized Link State Routing Protocol for Ad Hoc Networks, IEEE INMIC 2001, pp. 62-68.

[22] Hsieh HY and Sivakumar R, (2002). A Hybrid Network Model for Cellular Wireless Packet Data Networks, Proc. of IEEE GLOBECOM2002, Taipei.

[23] Wu H, Quiao C, De S, Tonguz O, (2001). Integrated Cellular and Ad hoc Relaying System: iCAR, IEEE J-SAC vol.19, no.10, pp.2105-2115.

[24] Carle J, Simplot-Ryl D, (2004). Energy-Efficient Area Monitoring for Sensor Networks, IEEE Computer Magazine, Vol. 37, No. 2, pp. 40- 46.

[25] Fujiwara T, Ulusoy HS, Feng MQ, (2011). Towards Low-Cost Structural Health Monitoring with Sensor Networks in Earthquake Damage Detection, Proc. of the 8th International Workshop on Structural Health Monitoring, Vol. 2, pp. 2012-2019, Stanford.

[26] Kim S, Pakzad S, Culler D, Demmel J,(2007). Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks, Proc. of the 6th International Conference on Information Processing in Sensor Networks, pp. 254-263, Cambridge.

[27] Fujiwara T, Watanabe T, (2005). An ad hoc networking scheme in hybrid networks for emergency communications, Elsevier, Ad hoc Networks, Vol.3, pp607-620.

[28] Fujiwara T,Shimazaki Y,Toyoshima H,Ito S,Sugiura M,Atsumi M,Watanabe T,Mizushina S, (2000). A TD-CDMA Data Collection System for City Lifeline Monitoring, Proc. of IEEE VTC2000-Spring, pp.1630-1635, Tokyo, May 2000.

[29] M.Sugiura, A.Adachi, T.Fujiwara, T.Watanabe, S.Mizushina et al., Wireless Data Acquisition for Post-Earthquake Lifeline Performance Monitoring, Proc. of APMC2000, Sydney.