Samrt Structures and Systems, *Vol. 11, No. 5 (2013) 497-510*
DOI: http://dx.doi.org/10.12989/sss.2013.11.5.497

A scheme on multi-tier heterogeneous networks for citywide damage monitoring in an earthquake

Takahiro Fujiwara*[1], Takashi Watanabe[2] and Masanobu Shinozuka[3]

[1]Depertment of Computer Engineering, Hakodate National College of Technology, Hakodate, Japan
[2]Graduate School of Science and Technology, Shizuoka University, Hamamatsu, Japan
[3]Department of Civil and Environmental Engineering, University of California Irvine, Irvine, U.S.A

(Received June 11, 2012, Revised November 25, 2012, Accepted November 30, 2012)

Abstract. Quick, accurate damage monitoring is strongly required for damage assessment in the aftermath of a large natural disaster. Wireless sensor networks are promising technologies to acquire damage information in a citywide area. The wireless sensor networks, however, would be faced with difficulty to collect data in real-time and to expand the scalability of the networks. This paper discusses a scheme of network architecture to cove a whole city in multi-tier heterogeneous networks, which consist of wireless sensor networks, access networks and a backbone network. We first review previous studies for citywide damage monitoring, and then discuss the feature of multi-tier heterogeneous networks to cover a citywide area.

Keywords: multi-tier networks; heterogeneous network; sensor networks; disaster damage monitoring

1. Introduction

Progress of computer networks and mobile communications are leading to the environments capable of accessing networks anytime, anywhere. People expect to be able to acquire necessary information through the Internet and to contact with family, friends, colleagues and others through communications systems as usual even in case of a disaster. However, we recognize in several instances of previous large-scale disasters that communications systems could not work normally due to heavy use, overload in networks and communications congestion, preventing quick efficient information gathering for damage assessment (Miller and Haas 2006, Fujiwara and Watanabe 2008, Allen 2005). As a result, response efforts were delayed, causing further damage that could be prevented with better communications. Such a communications issue of the networks during a disaster has yet to be overcome.

Several studies have been carried out to detect damage in a citywide area in case of an earthquake. A gas pipeline monitoring system was developed to observe the conditions of natural gas trunk pipelines, placing spectrum-intensified sensors at 3600 sites in Tokyo (Shimizu 2000). The system was capable of detecting damage in significant sites, and transmitting data via dedicated telecommunications lines without communications congestion. Another study on

*Corresponding author, Professor, E-mail: tkfujiwr@hakodate-ct.ac.jp

http://www.techno-press.org/?journal=sss&subpage=5 ISSN: 1738-1584 (Print), 1738-1991 (Online)

damage monitoring for citywide lifeline facilities was carried out with a dedicated wireless communications system, which was configured with a hierarchical network in CDMA (Code Division Multiple Access) (Fujiwara *et al*. 2000). The results showed that it was feasible to collect damage information within one minute from approximately 250,000 nodes installed in citywide lifeline facilities (Sugiura *et al*. 2000).

Such dedicated systems work well for the specified purpose though the operation cost should be increased. Wireless sensor networks (WSN), on the other hand, are promising technologies to flexibly acquire information for multiple purposes such as environmental monitoring and security information in a low cost. The WSN are also expected to detect and collect damage information in a disaster. However, it would be faced with difficulty to expand the scalability of the network and to collect data from a wide afflicted area in real-time. This paper discusses network architecture for damage monitoring combining sensor networks and access networks, hence heterogeneous networks, to collect data in real-time and to expand the scalability of the coverage in the citywide area. The concept of the damage monitoring system in multi-tier networks is shown in Fig. 1. We first review some related works for damage monitoring in Chapter 2, then describe a scheme of the multi-tier heterogeneous networks in Chapter 3. Some experimental results are shown in Chapter 4. Finally, we conclude this work.

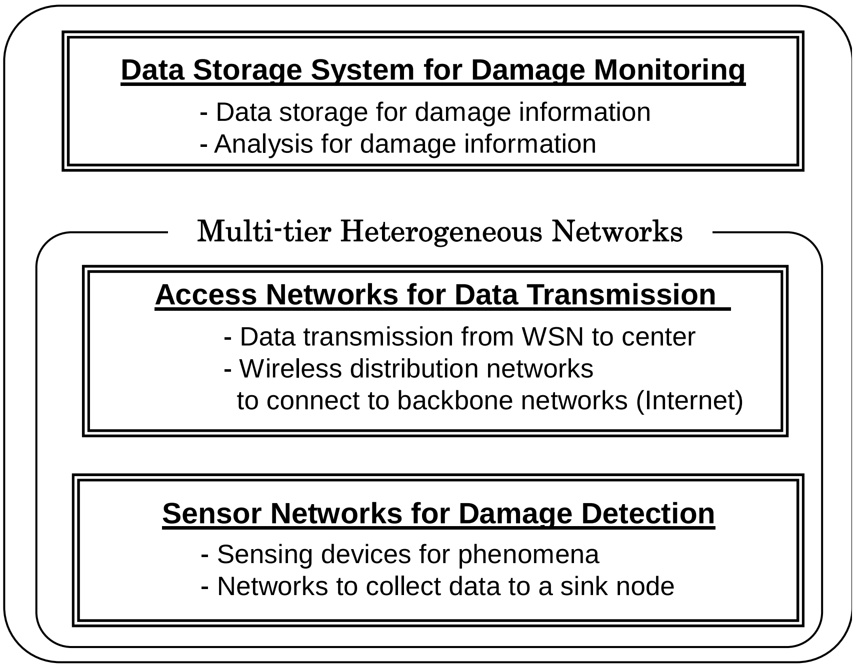


Fig. 1 Concept of damage monitoring system with Wireless Sensor Networks through Wireless Distribution Networks

2. Related works for damage monitoring

2.1 Lifeline wireless monitoring system in citywide area

A dedicated data collection system was designed and experimented to monitor city lifelines of gas pipelines and water pipelines (Fujiwara *et al*. 2000, Sugiura *et al*. 2000), The concept of the system is depicted in Fig. 2, which comprises two tier networks with the upper and lower to cover a total of 250 k terminals in an urban area of about 260 km^2. Fig. 3 shows the experimental model of a wireless communications system of two layers, and the air interface parameters are listed in Table 1.

The upper layer network was designed to covers a whole city with 1024 cells. The central control station (CS) accesses a base station (BS) of each cell with a TDM (Time Division Multiplexing) wireless system. The upper layer radio system employed a narrow-band radio communications of 2.1 GHz to connect between CS and multiple BS, where the output power is 1 W to cover an area of a long distance. The lower layer network, on the other hand, 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. Since the communications range was designed at 300 m, the output power was set up at 10 mW or less. Each station of CS and BS in the upper layer contains a database server, and 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 applications.

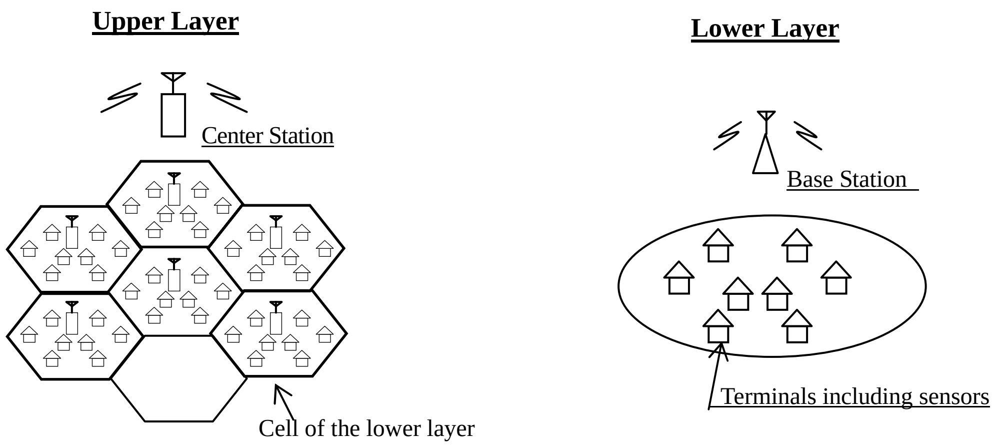


Fig. 2 A concept of a multi-tier data collection system to cover a citywide area

Experimental results showed that the total system of the upper and the lower networks was capable of collecting data of 20 bytes per terminal from 250k in about 7 minutes. Furthermore, the monitoring system is feasible to collect urgent data of 2 bytes from every terminal in approximately one minute Sugiura *et al*. (2000). That is, the experimental system is capable of acquiring damage conditions within one minute in a citywide area in a disaster. One concern is, however, that links between BS and nodes are vulnerable due to a single path. There is a highly potential issue that the propagation conditions of the wireless networks get worse by damage on a device or other interruptions.

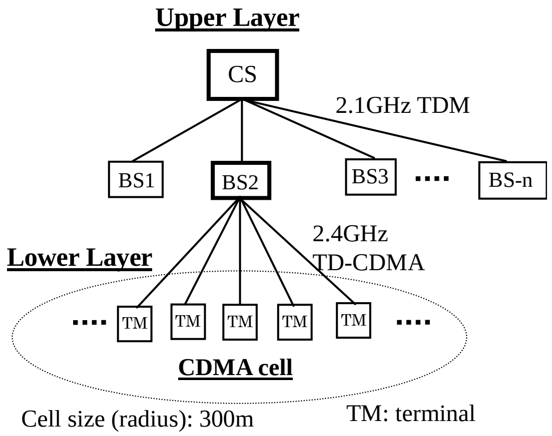


Fig. 3 An experimental model of a wireless communications system of two layers

Table 1 Parameters of air interface

	Upper Layer	Lower Layer
Radio Channel	Narrow band	CDMA
Access Protocol	Polling	TD-CDMA
Frequency	2.1 GHz	2.4 GHz
Bandwidth	150 kHz	1.5 MHz
Power	<1 W	<10 mW
Data rate	288 kbps	19.2 kbps
Range	≤ 10 km	≤ 300 m
Capacity	1024 stations	256 nodes

2.2 Hybrid wireless networks enhanced with ad hoc networks

A centralized wireless network connecting a base station (BS) and terminals directly and operating in polling mode is suitable to acquire data efficiently without communications congestion, as shown in the previous work. However, it should be a potential but obvious concern that nodes cannot access BS due to deterioration of propagation conditions. Meanwhile, ad hoc networks allow nodes to rebuild an alternative route dynamically even if an existing route might be disconnected (Royer and Toh 1999). The ad hoc network is actually flexible to build a route, but is not stable to maintain links due to interferences from hidden terminals, contention in communications or deterioration of propagation conditions. Furthermore, when the number of hops in the ad hoc network increases, route connectivity should be decreased. Consequently, the reliability of the network may degrade due to excessive multihopping. Those drawbacks hamper to disseminate ad hoc networks to emergency communications.

A concept of a hybrid wireless network shown in Fig. 4 was proposed (Fujiwara and Watanabe 2005), which combines a scheme of ad hoc network and a centralized network. Provided that the BS maintains direct connection to terminals, the centralized network acquires information from terminals stably. In the event that connections between BS and terminals are impaired, the BS cannot access the terminals directly, and then switches the mode to the ad hoc to connect through a neighboring node which is directly accessible to BS. The experimental results by computer simulation showed that approximately 90% of nodes can discover a route within a few hops, even if only 20% of nodes are able to access BS directly. However, the network is concerned about the impact of the node density to maintain the accessibility to the BS.

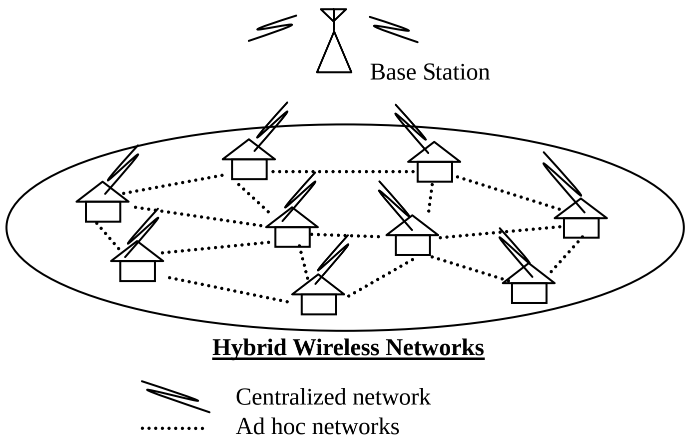


Fig. 4 Concept of hybrid wireless networks combining centralized and ad hoc networks

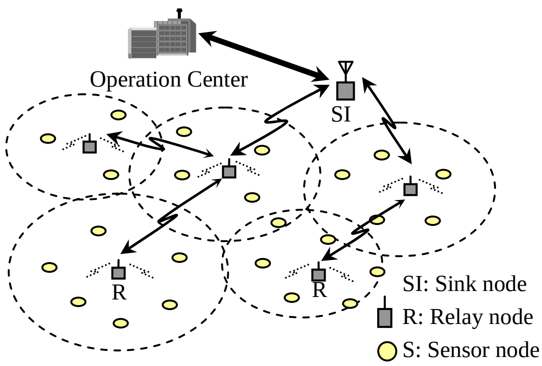
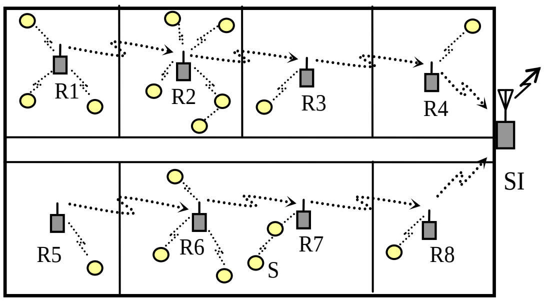


Fig. 5 System overview for damage monitoring with sensor networks



SI: Sink node, R: Relay node, S: Sensor node

Fig. 6 Deployment of sensor nodes to monitor conditions in a building

2.3 Wireless sensor networks for damage monitoring

Wireless sensor networks premise that massive sensor nodes are deployed in the field and build a network autonomously (Shen 2001). 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 operate by batteries, it is strongly required to reduce energy consumption (Demirkol *et al*. 2006). Assuming a seismic monitoring system, multiple sensor nodes are placed in buildings, bridges, or various structures in advance 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 of (Fujiwara *et al*. 2011) described a seismic acceleration observed in the University of California, Irvine, where the acceleration includes the signals of the bandwidth of around 30Hz on the ground and 5 Hz on the fourth floor. Thereby, the monitoring system is operating at the sampling rate of 200 Hz. Health monitoring of the Golden Gate Bridge was carried out with wireless sensor networks (Kim 2007). They achieved the monitoring of the vibration on the bridge by multi-hopping of 46 hops at a sampling rate of 1 KHz. From those studies, we have to consider in the monitoring system providing a long time operation and extending the coverage of damage monitoring especially in a large-scale disaster.

A model of the monitoring system configured with sensor networks is shown in Fig. 5, which collects information on the conditions of buildings, structures or lifeline facilities (Fujiwara and Watanabe 2008). The sensor networks are configured with sensor nodes to detect phenomena, relay nodes to forward data by multi-hopping and a sink node to gather data. A route from a node to the sink node is built autonomously by way of ad hoc networking techniques. An example on deployment of nodes in a building is illustrated in Fig. 6, where each node detects the conditions of rooms, lobby, or corridor. In case that unexpected occurrence happens, the network should quickly forward the information to the sink node through neighboring nodes and relay nodes by multi-hopping.

Although the sensor networks are expected to be capable of monitoring the conditions of damage in a disaster, we have to consider that the nodes are operating by batteries, resulting in sensitive operation by power consumption. The restriction induces a long latency to reduce the power. A MAC (Medium Access Control) protocol considering the latency to transmit data from a node to a sink node was proposed (Fujiwara and Watanabe 2010). The protocols showed it is feasible to operate in a short latency, resulting in quick data transmission. However, since the scale of the network was restricted, it might be difficult to cover a wide area.

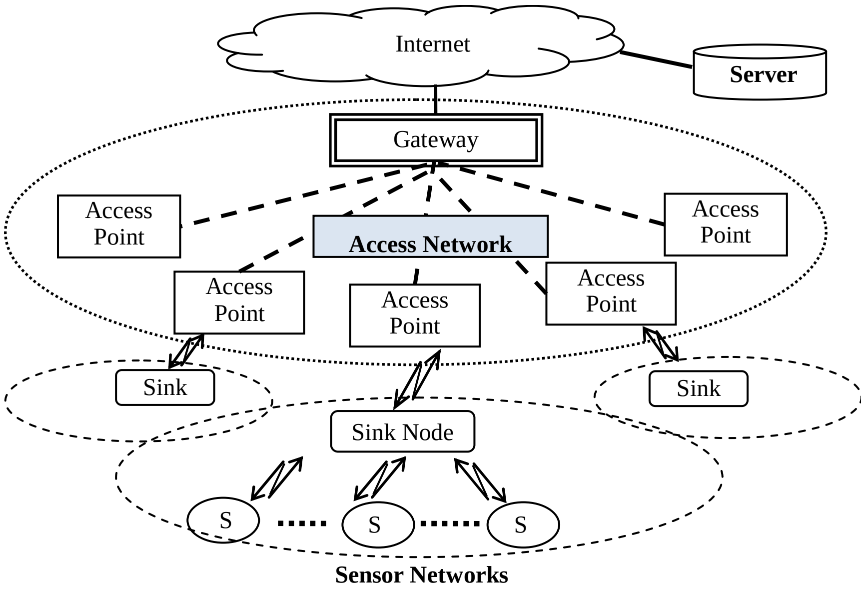


Fig. 7 A scheme of multi-tier heterogeneous networks for damage monitoring

3. Multi-tier heterogeneous networks for damage monitoring

The dedicated system would be capable of collecting damage information in a citywide area in a short period of time without communications congestion, as reviewed in previous section. Such dedicated systems, however, might be faced with issues on implementation or maintenance cost. The system with wireless sensor networks is capable of building a network autonomously and flexibly, and collecting data with low-cost devices in energy-aware scheme. In this section, we discuss a scheme of multi-tier heterogeneous networks for damage monitoring considering the coverage.

3.1 Overview

Wireless sensor networks are effective to detect phenomena and to collect data in a sink node, meanwhile the coverage is restricted due to a short communications range even if using multi-hopping. We show the model of the multi-tier heterogeneous networks for damage monitoring in Fig. 7, configured with wireless sensor networks and access networks. The system provides functions of damage detection and data collection with sensor networks, expansion of the coverage with access networks, and transmission of data to the database server through the Internet.

3.2 Wireless sensor networks

Assuming a wireless sensor network performs multi-hopping through other sensor nodes to forward data, the number of multi-hopping increases to expand the coverage. Such multi-hopping may induce a hard restriction to save the power and to fill the requirement of the short latency. In addition, since the communications range of one link is short, e.g., 20 m or 100 m at most, the length of multi-hopping is getting longer, inducing a long latency increasingly. Furthermore, convergence of traffics from nodes by multi-hopping is getting worse in the links around the sink node. Especially, in conditions where the network operates to detect earthquake acceleration, it should continuously transmit data to the sink node, resulting in a heavy traffic. To reduce the traffics in the network, the system has to reduce the number of nodes in a cell. That is, we have to consider the restriction of the sensor networks to monitor earthquake acceleration instead of the regular concept of sensor networks.

In Fig. 7, each sensor network contains a limited number of sensor nodes in a cell, resulting in a small coverage. That is, the monitoring system does not introduce a scheme for a great number of multi-hopping. In spite of the scheme to reduce the size of a cell, the system is required to expand the coverage. One solution to fulfill the requirement is a multi-tier heterogeneous network, configured with an access network, which provides high speed data transmission and expands the coverage.

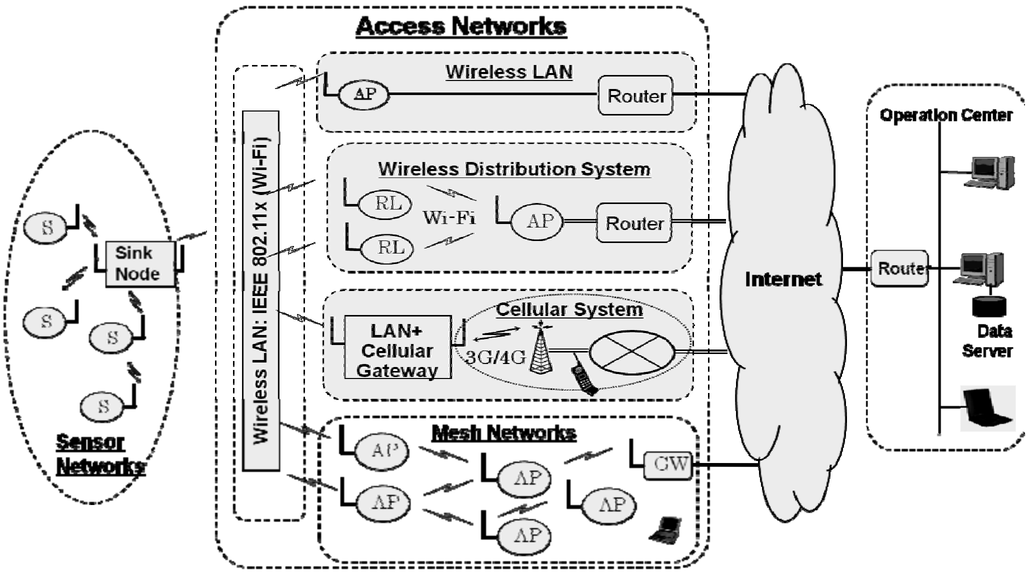


Fig. 8 A model on several types of access networks

3.3 Access networks

We can introduce several types of communications techniques in access networks to connect wireless sensor networks as shown in Fig. 8, assuming a communications unit in a sink node employs a standard of Wi-Fi (Wireless Fidelity) based on IEEE 802.11. We discuss four types of models, a regular wireless local area network (WLAN), a wireless distribution system (WDS), a cellular system with Wi-Fi interface, and wireless mesh networks.

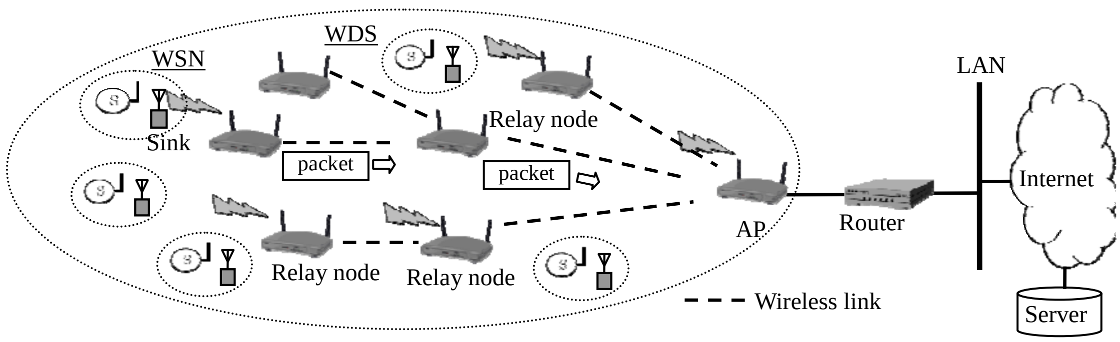


Fig. 9 A model of a wireless distribution system (WDS)

(1) Wireless Local Area Networks

A scheme of the WLAN type in access networks contains access points (AP) operating in Wi-Fi to communicate with sink nodes in wireless. Since the AP is connected to the router directly, this type of model is available to operate in a small area such as in a building, where we can use several ports of the local area network. Although the system of this type is easy to use inside a building, it does not consider expanding the monitoring area outside the building. Some WLAN systems actually operate out of doors; however, they operate in a single hop, and are not suitable for expanding the coverage.

(2) Wireless Distribution System

A wireless distribution system (WDS) is configured with an access point and multiple relay nodes as shown in Fig. 9. An access point (AP) is linked to neighbouring relay nodes (RN) by radio communications, and the neighbouring nodes are further linked to others. Finally the AP and multiple RN form a tree-structured topology. Since the connection between neighboring nodes is established by MAC (Medium Access Control) address of each node, this system operates based on Layer-2-switch. Thus, the WDS is capable of expanding the coverage of an access point in the wireless LAN by relaying communications packets.

(3) Cellular System with Wi-Fi Interface

A cellular system including a gateway with Wi-Fi interface can access surrounding sink nodes of sensor networks as shown in Fig. 10. The gateway node collects data from the sink nodes through Wi-Fi, and relays packets to the base station via the cellular system. And then, the cellular system transmits data to a database through the Internet. This type of system is effective to access a sink node which is located in a separated area. That is, in conditions where the distribution of the monitoring area is like an island shape in a rural area, and the sink node can access the gateway node by Wi-Fi even if the area stays away from the base station of the cellular system, the sink node is possible to transmit information to the database through the cellular system and the Internet. However, since the gateway operates in a single hop, the sink nodes should be located around the gateway within one hop. It is an issue to expand the monitoring area.

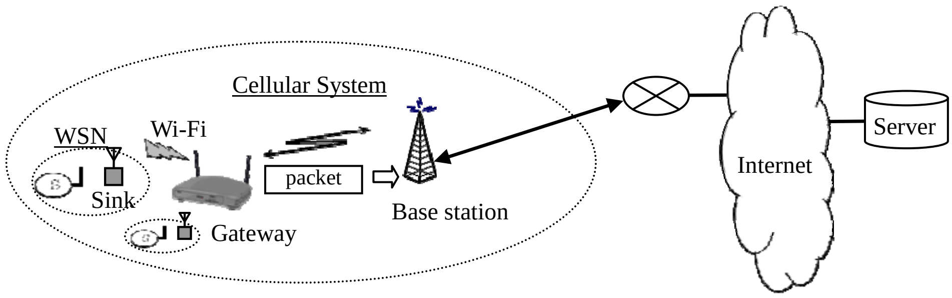


Fig. 10 A model of a cellular system with Wi-Fi interface

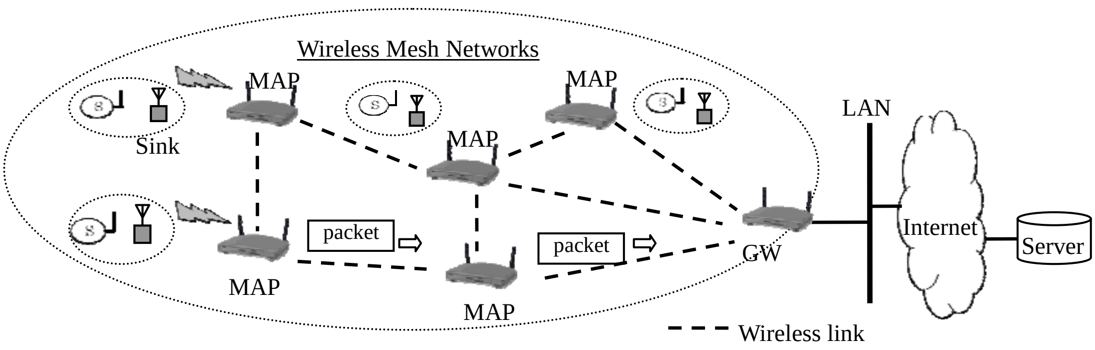


Fig. 11 A model of wireless mesh networks

(4) Wireless Mesh Networks

Wireless mesh networks have a feature to be able to self-organize and self-configure networks by ad hoc networking technologies. The networks are composed of a gateway (GW) and multiple mesh access points (MAP) like a mesh shape as shown in Fig.11, which are connected each other by Wi-Fi (Sakata *et al*. 2006, Akyildiz and Wang 2005). Since the mesh networks can find a route autonomously and flexibly, the networks maintain routes to access another node and expand the coverage. Provided that nodes of sensor networks are deployed in the area of wireless mesh networks and the sink node mounts a Wi-Fi interface, the sink node can transmit data to MAP, and then the data is forwarded through the gateway to a database server.

Table 2 Specification of Wi-Fi nodes

	Access Point	Relay Node
Model number	WHR-G301N	WLAE-AG300N
Standard	IEEE 802.11g	IEEE 802.11g
Frequency	2.4 GHz	2.4 GHz
Data Rate	54 Mbps (Max)	54 Mbps (Max)

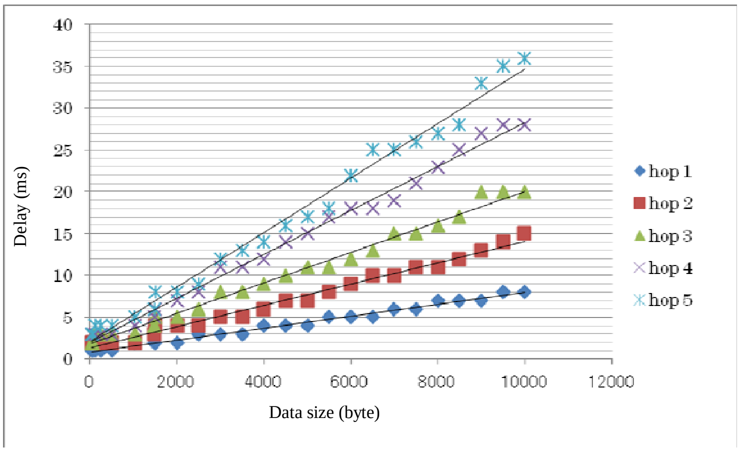


Fig. 12 Delay in hop-count as a function of data size

4. Evaluation

4.1 Delay and throughput of wireless distribution system

The experimental wireless distribution system (WDS) was installed by allocating four relay nodes (RL) and one access point (AP) in a series at each distance of 30 m, and the link of each node was set up by designating neighbor nodes with the MAC address. Table 2 lists the details of the experimental nodes operating in Wi-Fi. The experiments measured the delay to transmit data from a personal computer (PC) to the AP via RLs in multi-hopping, where the PC accesses a RL by Wi-Fi. The results are depicted in Fig. 12; increasing data size, delay proportionately increases, and as the number of hops becomes larger, the delay also increases. From these results, throughput of the WDS was calculated in each hop-count, and depicted in Fig. 13. In the case of one hop, the throughput is 23 Mbps. The system obtains a high throughput. Increasing the number of hop-count, the throughput is getting worse, and reaches 5 Mbps in five hops.

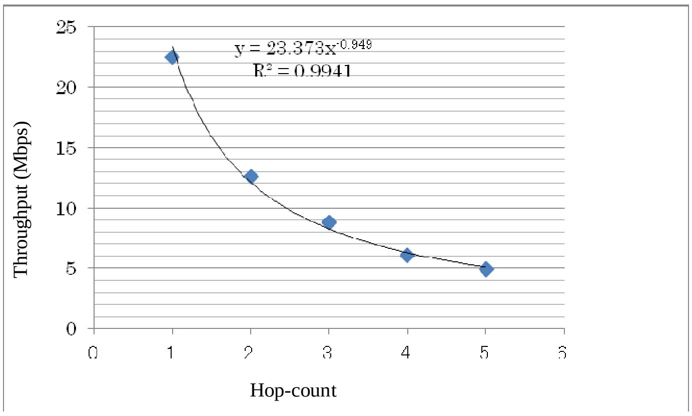


Fig. 13 Throughput as a function of hop-count

Table 3 Specification of WSN

Sink node	Crossbow/MIB600
Sensor node	Crossbow/XM2110J
Sensor board	Crossbow/MTS400
Standard	IEEE 802.15.4
Frequency	2.4 GHz
Data Rate	250 kbps

4.2 Throughput of wireless sensor networks

The experimental Wireless Sensor Networks (WSN) measured accelerations of two axes with MEMS devices installed in a sensor node, and continuously transmitted the data of 36 bytes to a sink node by one hop in wireless. Table 3 shows the specification of WSN, and Figure 14 shows the throughput. In conditions where the number of node is one and the sampling rate is 50 sampling per second (sps), all of the data were transmitted to the sink; thereby the throughput is 14,400 bps. In 100 sps, all of the data were also transmitted; that is, the throughput is 28,800 bps. However, in 125 sps, the throughput was 33,984 bps; some data did not reach the sink node. Increasing the number of nodes, the volume of lost data is increasing. These results imply that the throughput is limited at around 33,000 bps though the value is in some small measure. Even if assuming the maximum data rate of 250 kbps, the sampling rate of 100 sps and the data size of 36 bytes, the number of nodes should be only 8 nodes. That is, the sensor networks suffer the hard limitation in the number of nodes to monitor the earthquake acceleration. Thereby, data collection of acceleration requires high efficient data transmission, especially increasing the number of sensor nodes. That is the open issue yet.

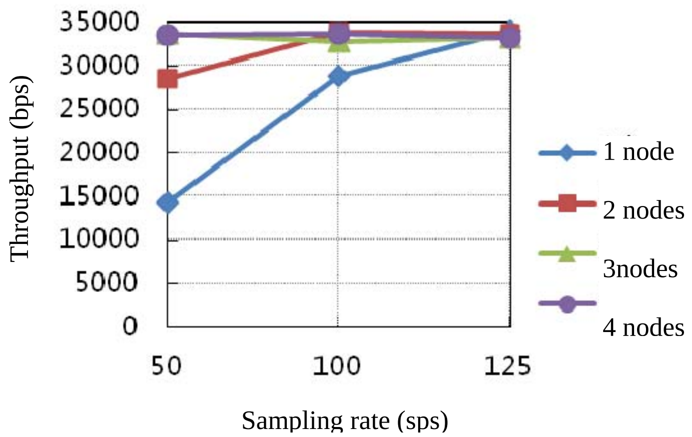


Fig. 14 Throughput of WSN as a function of sampling rate in measuring acceleration

5. Conclusions

We discussed damage monitoring with wireless sensor networks to expand the coverage in a citywide area, and investigated various types of network configuration. Considering damage monitoring in an earthquake, the monitoring system has to cover a whole city to assess damage conditions. This paper presented a scheme of multi-tier heterogeneous networks configured with wireless sensor networks, access networks, the Internet, and database servers. The total system for damage monitoring is required to cover a citywide area, and to collect information including earthquake acceleration in a short period of time. Introducing a Wi-Fi interface in a node of wireless sensor networks, the access networks easily acquire data from sensor networks. To expand the coverage, wireless distribution system (WDS) and wireless mesh networks (WMN) were considered. The experiments on WDS showed the system is capable of expanding the coverage by multi-hopping though the number should be limited. WMN should be also effective to expand the coverage, and provide a marked feature in flexible networking. On the other hand, to acquire earthquake acceleration by wireless sensor networks, the number of nodes brings a hard restriction in the volume of traffic, the experiments showed. For the future works, we need to study the way to improve the performance of the multi-tier networks to gather earthquake acceleration in a citywide area in a large-scale disaster.

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