High-Precision Monitoring System for Strong Earthquakes in Buildings Based on Distributed Intelligent Ad-Hoc Network

Xu Bai(✉), PengFei Feng, MingJie Ji, Yang Zhang, and ShiZeng Guo

School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, China
x_bai@hit.edu.cn

Abstract. Since the 20th century, the death toll caused by earthquakes in China has accounted for about half of all natural disasters in the country where the building collapse is the main cause of casualties. Therefore, it is an important issue for human society to recognize the mechanism of earthquake waves destroying buildings and design more earthquake-resistant building structures. We have developed and implemented a low-power, high-reliability and high precision earthquake monitoring system that can be deployed in buildings. The monitoring system uses high-precision sensors to collect the vibration information of each node of the building in real time, and save it in the local memory in real time, and at the same time make real-time judgments on the sampled information. When an earthquake occurs, the terminal acquisition node of the monitoring system will use the Lora ad hoc network to upload the vibration data before and after the earthquake to the cloud platform. After testing, the results show that the monitoring system operates stably in a strong earthquake environment and can provide data support for the seismic design of buildings in the future.

Keywords: Earthquake monitoring · Data acquisition · Ad-Hoc

1 Introduction

China is located between the Pacific Rim Earthquake and the Eurasian Seismic Belt, with high seismic activity frequency and high intensity [1]. This poses a serious threat to the safety of people's lives and property. Statistics show that since the 20th century, the number of people who died in earthquakes in China has reached 550,000, accounting for half of the total number of deaths due to natural disasters in the country. The main cause of casualties in the earthquake was the collapse of houses. In the 2010 Yushu earthquake in Qinghai, more than 85% of the houses collapsed. Many people were buried under the damaged houses, causing a large number of casualties and economic losses [2]. In recent years, high-rise buildings and super high-rise buildings have continuously appeared in China. They have higher sensitivity and vulnerability to earthquake disasters. Once they collapse, they will cause more serious consequences. Therefore, there is an urgent need to develop an earthquake monitoring system to measure the relative movement of buildings when an earthquake occurs, to establish an

Q. Guo et al. (Eds.): WiSATS 2021, LNICST 410, pp. 641–653, 2022.
https://doi.org/10.1007/978-3-030-93398-2_56

ideal mathematical analysis model, and to enhance the understanding of the mechanism of earthquake wave damage to the building, so as to design a more reasonable earthquake-resistant building structure. Minimize the damage caused by the earthquake to the lowest possible extent [3]. For example, the United States has established an earthquake disaster mitigation network, ANSS system and NEES system [4]. The system is equipped with about 7,000 seismic stations and sensors to measure the response of the ground and buildings to earthquake vibrations, build a seismic information database, and provide the data to the architectural design engineer in order to build stronger earthquake-resistant houses [5].

When monitoring the degree of damage to a building structure by an earthquake, the structural dynamic response information is usually obtained by measuring structural vibration information, and various data characteristics contained in the structural dynamic response information are analyzed. Therefore, the seismic monitoring system is mainly to collect the vibration information of the building. Dense distributed sensors are critical to the efficiency of vibration-based damage identification. With the emergence of high-rise buildings and super high-rise buildings, it is necessary to set up more monitoring points for these buildings, and the distance between different monitoring points is also increasing, which causes the actual wiring to be time-consuming and laborious. At the same time, in a complex building environment, compared to wireless solutions such as Wi-Fi and Bluetooth, the wireless solution based on the Lora (Long Range) protocol has more advantages in anti-interference and transmission distance, so the earthquake monitoring system uses Lora wireless Ad Hoc Networks which makes the layout of the monitoring system terminal more convenient and faster [6–8].

2 Function Realization

2.1 System Structure Model

We aim to design a low-power, high-reliability earthquake monitoring system that can be deployed in buildings. The system is mainly composed of three parts, namely the terminal acquisition node, the cloud server and the user platform. As shown in Fig. 1. In order to save resources and reduce costs, the acquisition nodes arranged in close positions use the Lora module to perform ad-hoc networking to transmit data. There are one or more terminal acquisition nodes installed with 4G modules in the same networking. The data of each node in the network is aggregated and uploaded to the cloud server. Researchers can download the vibration information of each node of the building by accessing the cloud server and analyze the data to design a more earthquake-resistant building.

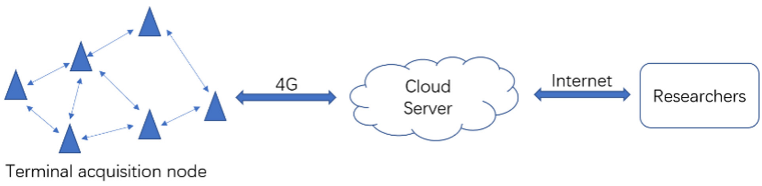

Fig. 1. Overall system structure

The specific structure diagram of the acquisition node is shown in Fig. 2, which includes a three-degree-of-freedom acceleration sensor, low-pass filter, A/D sampling module, single-chip microcomputer main control chip, storage Flash, Lora module and 4G module.

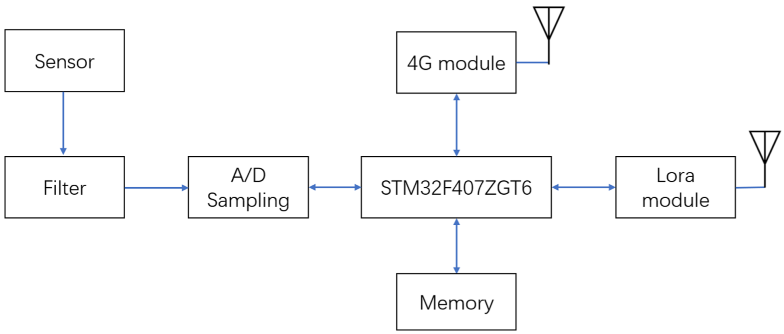

Fig. 2. The structure diagram of the acquisition node

The system uses a dual-power adaptive switching power supply module, daily use of city electricity to supply power for each terminal acquisition system and charge the backup battery, so when a high-magnitude earthquake occurs, the urban power system is destroyed, and the power supply system automatically switches to the backup battery for power supply.

The software implementation of the system is written by C language. In order to facilitate software writing, debugging and management, software programming adopts a modular structure, which mainly includes an initialization module, an acquisition module, a data storage module, and a data transmission module. The flow chart is shown in Fig. 3.

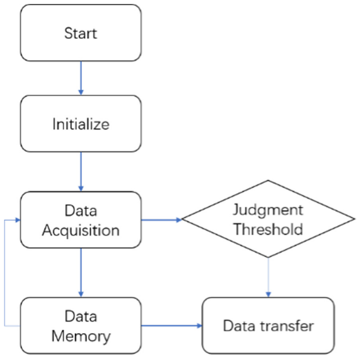

Fig. 3. Program flow diagram

2.2 Data Acquisition

The sensor converts vibration information in the three directions of X, Y, and Z into three analog voltage signals. The output voltage signal is usually a mixed signal of effective signal and interference noise. The response of buildings to earthquake vibration is often a low-frequency signal, which has the characteristics of large amplitude, concentrated energy, and slow signal change over time. Generally, it will not exceed 100 Hz. So it needs to go through a 100 Hz low-pass filter first to filter out high-frequency noise. Then the voltage signal is sent to the A/D sampling chip for sampling. The A/D converter selects the AD4111 chip, which is a low-power, low-noise, 24-bit Σ-Δ analog-to-digital converter. The chip can support 4 differential or 8 single-ended sampling channels. Support the maximum channel scan rate of 6.2 kSPS. When the A/D is sampled at a sampling rate of 200 Hz per channel, after testing, the root mean square noise is 27 μV, and the effective resolution calculation formula is:

$$6.02N + 1.76 = 20\log(noise/FSI) \tag{1}$$

It can be calculated that the effective resolution can reach 19.5 bit. Satisfy the speed and accuracy requirements for collecting building vibration data.

When the acquisition node stores and transmits the sampled data, it uses binary text for storage to save storage addresses. The frame format of each frame is shown in Table 1, including the address of the current acquisition node, the time of acquisition, the data in the three directions of X, Y, and Z, and the data synchronization bit.

Table 1. Frame format

Address	Time	X channel	Y channel	Z channel	Sync
2 bytes	4 bytes	3 bytes	3 bytes	3 bytes	1 byte

The acquisition time is set to 4 bytes, including 1 byte each for hour, minute, second, and sub-second. After sampling the three channels, by accessing the MCU's internal real-time clock register, the current time of the sampled data can be obtained, and the data can be time-labeled to facilitate the researcher to analyze the data. The data of the X, Y, and Z channels are 24-bit offset binary (offset binary). The code generated by full-scale negative voltage is 000…000. The code generated by zero differential input voltage is 100…000. The code generated by the full-scale positive voltage is 111…111. The output code of any analog input voltage can be expressed as:

$$Code = 2^{N-1} \times ((V_{IN} \times 0.1/V_{REF}) + 1) \tag{2}$$

where N = 24, V_{IN} is the analog input voltage, V_{REF} is the reference voltage, 2.5 V is selected as the reference voltage in this system and set 0x0A as the data synchronization bit at the end of each frame of data, which is convenient for researchers to process the sampled data.

2.3 Data Transmission

Since the time without an earthquake takes up a larger proportion, the information sampled at these times is useless. If the terminal monitoring node continuously sends out the sampled data, it will not only cause greater power consumption, but also occupy more channel resources, which limits the number of nodes in the local network. Therefore, when there is no earthquake, only a small amount of data is sent to the cloud to mark normal working nodes, and to check and repair abnormal working nodes in time. At the same time, real-time threshold judgment is performed on the data sampled by the terminal acquisition node. When the acceleration amplitude exceeding the threshold is sampled, start counting and observe the data sampled for the next 100 times. If 30 of the sampled data also exceed the threshold, it is considered that the node is indeed shaken, and a packet indicating the occurrence of an earthquake is sent to the sink node. If the sink node receives data packets indicating the occurrence of an earthquake by multiple nodes in the network for a period of time, it is considered that an earthquake has occurred, and the nodes in the network are ordered to send the data sampled 30 s before and after the earthquake. If only a data packet indicating the occurrence of an earthquake is received from a node.it is considered that no earthquake has occurred, This vibration caused by other reasons, such as house decoration.

When an earthquake occurs, it is inevitable that some terminal nodes will be disconnected, especially when the acquisition node with 4G function is damaged, it will affect all the acquisition nodes under the node, resulting in the loss of a large amount of sampled data. In order to minimize the loss caused by node damage, the system adopts the AODV protocol dynamic routing networking method [9]. When the route is broken, the RREQ (Route Request) message is sent out in the form of multicast to find a new path, so as to send the sampled data (Fig. 4).

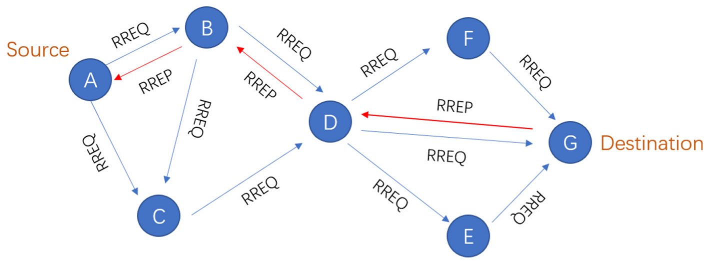

Fig. 4. Route discovery process

When an earthquake occurs, when the power of the terminal acquisition node is cut off, only a backup battery can be used for power supply. When some nodes whose communication is cut off may need to work longer, and wait for the communication to resume to transmit data. Reducing energy consumption is an effective way to extend the survival time of nodes. However, in actual engineering, in order to facilitate deployment and management, the transmit power of each node is the same. Although this setting reduces the complexity of the routing protocol. if the two nodes are relatively close, the data packet is still sent with a fixed maximum power. This caused a certain amount of energy waste. The path selection in the traditional AODV protocol is based on the minimum number of hops and does not consider the issue of network power consumption. But the least number of hops does not mean the shortest path and the least energy consumption, so the traditional AODV protocol is not suitable for this system.

Therefore, we have improved the traditional AODV protocol, and changed the route selection based on the least number of hops to the route selection based on the least energy consumption.

If you want to get the least energy consumption route, firstly, you should modify the RREQ data packet, and change the hop count in the original RREQ data packet to the sum of energy consumption. And the newly added Sending Energy table item, Sending Energy represents the power forwarded by the node, the newly modified RREQ data packet structure is shown in Table 2.

Table 2. Packet format of RREQ

Type	Reserved	Prefix Sz	Sum of energy
Sending energy			
RREQ ID			
Destination IP address			
Destination sequence number			
Originator IP address			
Originator sequence number			

RREP (Route Response) is to inform the route from the source node to the destination node that sends the RREQ message. There is also a function in the improved AODV protocol, which is to tell the destination node the total power consumed on the path, and at the same time tell the previous node through the reverse route The minimum transmit power. The newly modified RREP packet structure is shown in Table 3.

Table 3. Packet format of RREP

Type	Reserved	Prefix Sz	Sum of energy
Sending energy			
Destination IP address			
Destination sequence number			
Originator IP address			
Originator sequence number			
Lifetime			

Each node in the network must maintain a routing table. If a route is to be selected according to the minimum energy consumption, the original routing table must be modified. Change the number of hops to the destination node to the sum of the energy consumption to reach the destination node. Sending Energy is a copy of the Sending Energy table entry from RREQ, which indicates the transmitting power of the node, and the routing table structure is shown in Table 4.

Table 4. Routing table entry fields

Destination IP address
Destination sequence number
Interface
Routing flags
Sending energy
Sum of energy
Next hop
List of precursors
Lifetime

When the source node cannot find the legal route of the destination node, the route establishment process is performed. Send RREQ data packets with increasing transmit power (21 dBm, 24 dBm, 27 dBm and 30 dBm) respectively, and fill in the corresponding sending power value in the Sending Energy bit of RREQ, and calculate the value of Sum of Energy.

When a node receives an RREQ packet, it will determine whether it has received an RREQ message with the same source IP address and RREQ ID in the past period of time. If not, search the local routing table to see if there is a reverse route to the source IP address. If not, establish a reverse route. The process of establishing and updating the reverse route is as follows:

1. Compare the sequence number of the source node in the RREQ with the entry in the routing table whose destination IP is the source node, and update the sequence number in the routing table to the maximum value of the two.
2. The next hop field in the corresponding entry of the routing table is set to the IP address of the previous node that received the RREQ message.
3. The Sum of Energy value in the corresponding entry of the routing table is modified to the Sum of Energy value in the RREQ packet, and the Sending Energy value of the RREQ packet is copied into the Sending Energy entry of the routing table.

If it is not the first time to receive the RREQ packet, compare the value of Sun of Energy in the RREQ packet with the value of Sum of Energy in the corresponding entry in the routing table. If the value of Sun of Energy in the RREQ packet is smaller than the value of Sum of Energy, the reverse routing table is updated. However, updating the reverse routing table this time does not modify the sequence number in the routing table. Then the RREQ data packet is forwarded with the transmission power from small to large, and the Sending Energy value of the RREQ data packet is filled with the corresponding transmission power value to calculate the Sum of Energy value. If the Sum of Energy value in the RREQ data packet is greater than the Sum of Energy value in the reverse routing table, the RREQ data packet is discarded to avoid repeated processing.

Nodes will generate RREP packets in two situations. The first is that the node is the destination node. At this time, RREP packets will be generated and unicast back to the sending node through the reverse route. Another situation is that the current node is an intermediate node and there is a route to the destination node, then fill in the RREP according to the destination node serial number, Sum of Energy, Sending Energy in the routing table, and unicast back to the sending node through the reverse route.

When the link is cut, all adjacent nodes using the link will generate a RERR message to inform other nodes of the link failure. At this time, the affected node needs to initiate a new route request to find a new path. Before finding a new path, the data needs to be saved locally.

After experimental testing, in the same environment, using the improved AODV protocol to transmit data can save 40% of the power consumption and greatly extend the life span of each node.

When using the AODV protocol dynamic routing networking mode, the MAC layer usually selects CSMA/CA (Carrier Sense Multiple Access/Collison Avoidance) technology to avoid data packet collisions on a single shared channel as much as possible [10]. However, the CSMA/CA algorithm only uses a simple binary exponential backoff algorithm, and does not consider the network conditions. However, when an earthquake occurs, all nodes in the network will start uploading a large amount of data at the same time, which greatly increases the probability of collision, which leads to data loss, and reduces the throughput of the network and increases the delay. So we need to improve the MAC layer protocol, the improvement plan is as follows:

When the earthquake does not occur, the amount of data is small, and only a small amount of data is transmitted at intervals. At this time, the MAC layer adopts the CSMA/CA protocol to avoid data packet conflicts under the same channel. When an earthquake occurs, the nodes in the network must send data to the nodes with 4G function, and the amount of data is relatively large. At this time, the MAC layer adopts the token passing protocol [11]. Only nodes with tokens in the network can send data.

In order to evaluate the program, we use 10 sets of devices to network through the AODV protocol, of which nine sets of devices simultaneously send 100 data packets to the tenth set of devices, each with a size of 1024 bytes. In the same environment, the CSMA/CA protocol and the token protocol were used for testing. The experimental results are shown in Table 5.

Table 5. Collision test of CSMA/CA and token passing

Device	CSMA/CA	Token passing
Device 1	83/100	100/100
Device 2	87/100	100/100
Device 3	80/100	100/100
Device 4	91/100	100/100
Device 5	94/100	100/100
Device 6	78/100	100/100
Device 7	86/100	100/100
Device 8	90/100	100/100
Device 9	85/100	100/100
Total time	19 min	14 min

The test results show that: when an earthquake occurs, the MAC layer uses the token passing protocol instead of the CSMA/CA protocol, which not only avoids data packet collisions, but also has a higher channel utilization rate and can upload data to the cloud server with shorter data.

3 Test and Result Analysis

In order to verify the effectiveness of the monitoring system, we carried out a working condition verification in the model building shown in Fig. 5. The ground vibration table applied different magnitudes of acceleration in the X and Y directions of the building model. To simulate the seismic excitation that causes the building to vibrate. We arrange the acquisition equipment on the top of the first floor. The acquisition equipment will only send out the data of 30 s before and after the shaking when the seismic excitation is applied by the shaking table. After the later software reads the vibration data uploaded by the acquisition node, the acquisition waveform is shown in Fig. 6.

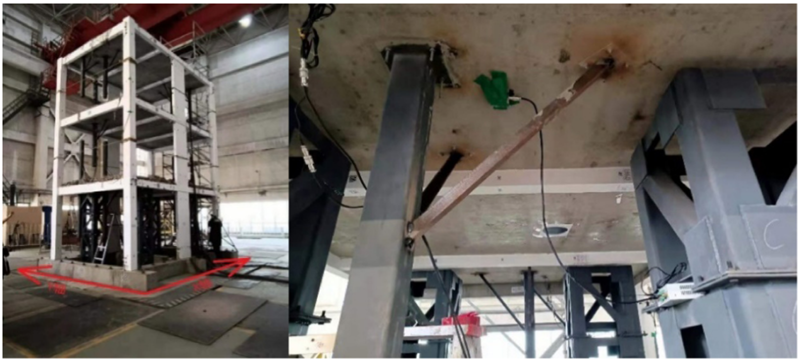

Fig. 5. Vibration data acquisition of building model

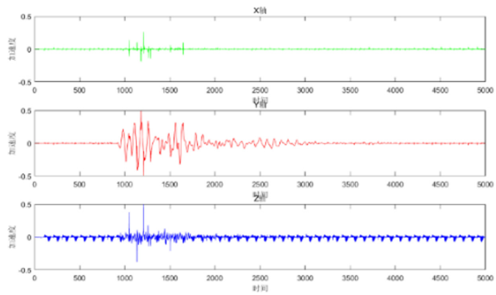

Fig. 6. The acquisition waveform of acceleration excitation with a peak value of 400 cm/s^2 is applied to the Y-axis of the building

This is the case of no interference, and it can be seen that the waveform is clearer and the noise is small. Then we add interference noise to the equipment, and the acquisition waveform is shown in Fig. 7. It can be seen that there is a lot of noise in the acquired waveform. Since noise is generally steady-state noise, it does not change with time in a short period of time. Therefore, we perform time-domain windowing and intercept the second half of the waveform without excitation for spectrum analysis. The spectrum analysis is shown in Fig. 8. It can be distinguished that the useful signal is at a low frequency, while the frequency of the noise signal is mainly concentrated around 80 Hz. So we can filter out noise by designing a filter, and the filtered signal waveform is shown in Fig. 9. It can be seen that the noise of each channel is obviously suppressed, and a better acquisition waveform can be obtained.

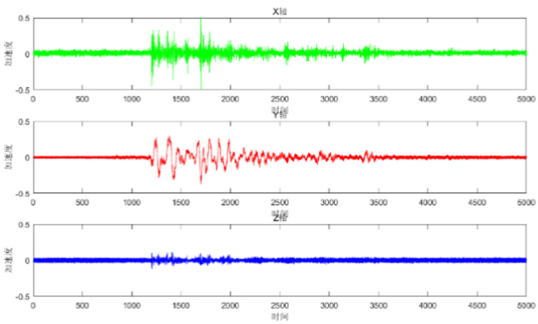

Fig. 7. In the presence of noise, the acquisition waveform of acceleration excitation with a peak value of 400 cm/s^2 is applied to the Y-axis of the building

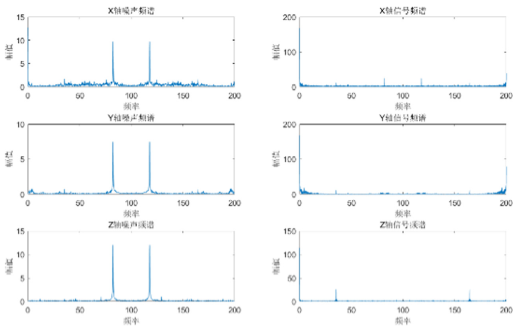

Fig. 8. Spectrum analysis

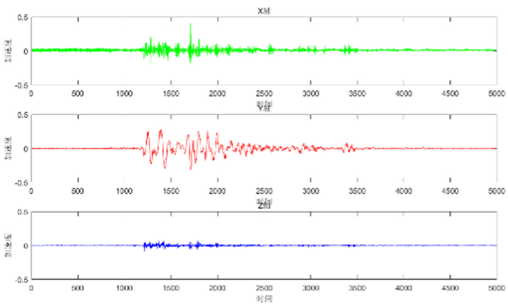

Fig. 9. Waveform after filtering the acquired data

The test results show that the system can judge the time of the earthquake through the threshold, and completely transmit the data sampled 30 s before and after the earthquake. It can be seen from the software to output the waveform that the waveform sampled is clearer without interference, and the sampled data conforms to the actual vibration situation of the building. Even if the acquisition system is disturbed due to some reasons, it can be better filtered out to get the original waveform.

4 Conclusion

The building vibration acquisition system designed in this paper has the characteristics of low cost, low power consumption and high reliability. Instead of uploading all the sampled data to the cloud server, through multiple threshold judgments on the sampled data, only the data of 30 s before and after the earthquake is uploaded. It not only reduces the power consumption of the system, but also avoids occupying channel resources to transmit a large amount of useless information, and improves the node capacity of the network. This makes it possible to densely arrange acquisition nodes in the monitored building, and use the multi-node vibration information of the building to identify damage to the building, so as to realize all-weather real-time dynamic monitoring of the building. At the same time, in view of the high destructiveness of earthquakes, AODV dynamic routing networking is adopted. Even if some nodes are damaged, data can still be transmitted in a multi-hop manner, which reduces the possibility of data loss and communication interruption, and greatly improves the robustness of the system. The test results show that the system can accurately and stably record the vibration information of the building when the earthquake occurs. Adopting the Ad-Hoc network method greatly reduces the data loss rate during transmission. The monitoring system collects the vibration information of each node of the building when an earthquake occurs, thereby constructing an earthquake information database, which is of great significance to the design and construction of buildings with stronger earthquake resistance in the future.

Acknowledgment. Supported by the National Key R&D Program of China (No. 2017YFC1500601.)

References

1. Xu, W., Liu, J., Xu, G., Wang, Y., Liu, L., Shi, P.: Earthquake disasters in China. In: Shi, P. (ed.) Natural Disasters in China. IERGPS, pp. 37–72. Springer, Heidelberg (2016). https://doi.org/10.1007/978-3-662-50270-9_2
2. Zheng, J., Liao, Y., Du, L., Niu, J.: Investigation and analysis of building damage in Yushu city caused by earthquake. Build. Struct. **A1**, 1002–1054 (2013)
3. Goulet, J., Michel, C., Kiureghian, A.D.: Data-driven post-earthquake rapid structural safety assessment. Earthquake Eng. Struct. Dynam. **44**(4), 549–562 (2015)
4. U.S. Geological Survey. Advanced national seismic system-current status, development opportunities, and priorities for 2017–2027. Translated World Seismolog. **49**(5), 397–424 (2018)

5. Elnashai, A., Di Sarno, L.: Fundamental Concepts of Earthquake Engineering. Wiley, Hoboken (2008)
6. Raza, U., Kulkarni, P., Sooriyabandara, M.: Low power widearea networks: an overview. IEEE Commun. Surv. Tutorials **19**(2), 855–873 (2017)
7. Augustin, A., Yi, J., Clausen, T., Townsley, W.M.: A study of LoRa: long range and low power networks for the Internet of Things. Sensors **16**(9), 1466 (2016)
8. Sinha, R.S., Wei, Y., Hwang, S.-H.: A survey on LPWA technology: LoRa and NB-IoT. ICT Express **3**(1), 14–21 (2017)
9. Perkins, C., Belding-Royer, E., Das, S.: RFC3561: ad hoc on-demand distance vector (AODV) routing (2003)
10. Trinh, L.H., Bui, V.X., Ferrero, F., Nguyen, T.Q.K., Le, M.H.: Signal propagation of LoRa technology using for smart building applications. In: 2017 IEEE Conference on Antenna Measurements and Applications (CAMA), pp.381–384. IEEE, December 2017
11. Moraes, R., Vasques, F., Portugal, P., Fonseca, J.A.: VTP-CSMA\CA virtual token passing approach for real-time communication in IEEE802.11 wireless networks. IEEE Trans. Ind. Inform. **3**(3), 215–224 (2007)