# Development of a multi-hop wireless sensor system for the dynamic event monitoring of civil infrastructure and its extension for seismic response monitoring

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# Abstract

The dynamic response of civil infrastructures under transient dynamic events is of particular interests for structural engineers, because these event-induced responses usually provide useful insights into the real dynamic behavior of civil infrastructures under extreme conditions. Monitoring these dynamic event induced vibrations are among the most frequently conducted measurements and experiments in the structural engineering field, and a cheaper, simpler and more flexible monitoring system is always under pursuit of civil engineers. One particular such request comes from the seismic response monitoring applications. Seismic response monitoring for general civil infrastructure is critical in high-risk earthquake areas like Japan. It contributes to earthquake safety by providing quantitative measurement that enables improved understanding and predictive modeling of the earthquake response of these engineered systems. However, due to the limitations of the current monitoring systems, such seismic response records of general civil infrastructure are usually not available.

Therefore, this research describes a novel development of an autonomous dynamic event monitoring system using Wireless Smart Sensor Network(WSSN), which is further extended to support the purpose of long-term seismic response monitoring. This developed WSSN monitoring system is portable and low-cost, it has a potential to provide long-term seismic response monitoring for a wide range of civil infrastructure. This system can run on existing power sources readily available in common civil infrastructure and thus is able to perform long-term continuous sensing as demanded by the seismic response monitoring applications. A quick and stable event detection method is developed to trigger the recording of the complete seismic response and also eliminate possible false alerts caused by unexpected disturbance. Long-term network-wide time synchronization is guaranteed by a customized long-term Flooding Time Synchronization Protocol(FTSP) so that the all sensor nodes in the network can provide consistent time records of their captured seismic response. An efficient multi-hop service module is also incorporated into the system to disseminate commands and accommodate the need of collecting data in a reliable and prompt manner after major earthquakes, the integrated multi-hop data collection protocol provides a theoretically optimum data collection efficiency. Various experiments have been done to validate the developed programs. Suggestions are also given towards the final realization of successful long-term implementation of the developed monitoring system.

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# Contents

# List of Figures

# Chapter 1

# Introduction

The dynamic response of civil infrastructures under transient dynamic events is of particular interests for structural engineers, because these event-induced responses usually provide useful insights into the real dynamic behavior of civil infrastructures under extreme conditions. These events under consideration range from moving vehicle loads, strong wind loads to possible earthquakes, and each of them is closely related to an essential aspect of our infrastructure design. For example, bridge vibration induced by moving vehicles is important to investigate the dynamic impact factor which is critical for the bridge fatigue design, the strong wind induced vibration of long-span bridge is of primary importance for the bridge wind-resistent design, and of course, records of seismic response can be used to facilitate the improvement of our aseismic design. Therefore, monitoring these dynamic event induced vibrations of civil infrastructures are among the most frequently conducted measurements and experiments in the structural engineering field, and a cheaper, simpler and more flexible monitoring system is always under pursuit of civil engineers. One particular such request comes from the seismic response monitoring applications. As is known, the traditional wired seismic response monitoring systems, hindered by their high cost associated with wiring and maintenance, have only limited applications, the deployments of these systems are permanent and only available for a very few number of instrumented infrastructures.

One scathing example of the deficiency of the current seismic response monitoring systems is the March 11th earthquake of 2011 in Japan, during which many civil infrastructures suffered from severe damages, however, few records of their seismic response were available due to the limited implementations of the current monitoring systems. The lack of seismic records posed difficulty for post-earthquake analysis and also deprived us the valuable chance to gain deeper insights into the real seismic behavior of a wide range of civil infrastructures that support our lives and society.

Therefore, a cheaper and more flexible monitoring system for the seismic response of civil infrastructures which is suitable for wide and general installation is needed. Such a system that can be easily installed on common civil infrastructures for a long-term, will be capable to provide engineers a powerful tool to obtain the valuable seismic response records from a variety of targets as well as to facilitate the improvement of our aseismic design.

This research seeks to develop such a cheaper, simpler and more flexible monitoring system using Wireless Smart Sensor Network(WSSN), for general dynamic event monitoring of civil infrastructures, and with special extension for the ultimate goal of seismic response monitoring. Since the main difficulties of developing such a system comes from the seismic response monitoring, and a system capable of performing seismic response monitoring can be easily adopted to monitor other transient dynamic events, the following developments are primarily oriented for the purpose of seismic response monitoring.

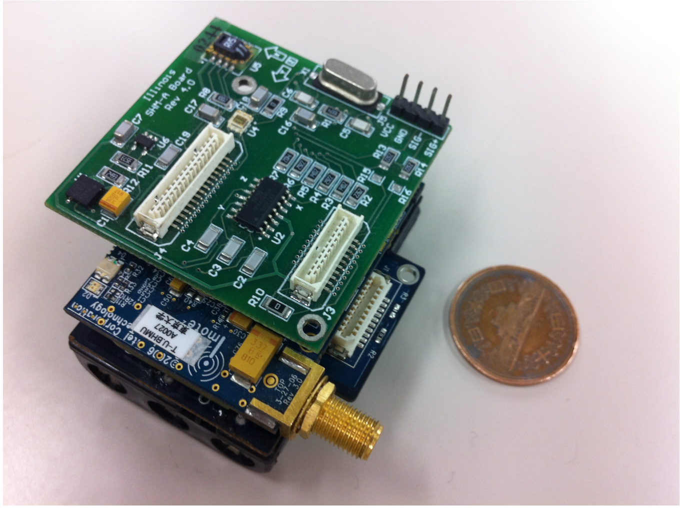

Figure 1.1: A wireless smart sensor node

## 1.1 Wireless Smart Sensor Network

The recent development of Wireless Smart Sensor Network(WSSN) has suggested a potentially low-cost and more resilient alternative for the dynamic monitoring of civil infrastructures. Basically, a WSSN is composed of a group of wireless smart sensors, as shown in Fig.1.1, the sensors are distributed spatially and communicate with each other through wireless communication radios to form a integrated functional network. Also, equipped with on-board computational power, each sensor unit in the WSSN can perform local and independent data processing, providing more opportunities for fully autonomous monitoring systems.

A number of researchers have proposed the usage of WSSN in the field of Structural Health Monitoring(SHM)(2)(3)(4)(5)(6)(7). Their works have proved the efficacy of this new monitoring strategy. As a summary, WSSN monitoring systems have the following advantages in comparison with traditional wired monitoring systems:

- It has low-cost associated with cabling and maintenance. Traditional monitoring systems include a number of delicate sensor units, a central station for data processing and power supply, and many cables to connect them to form a network, each of these components requires proper attention and maintenance, cost for implementing such a system is inevitably high since heavy human power is involved as well as expensive equipments are required. In comparison, WSSN completely eliminates the need for cabling, maintenance is also reduced to minimum given each sensor unit can be independent both spatially and functionally. And only cost for sensors itself is basically essential for establishing a WSSN monitoring system.

- It provide an ease of deployment, instead of trying to connect wires between sensors and central station which can be very cumbersome when sensors are widely distributed, installing wireless sensors simply requires putting them in the right locations and adjusting the antennas. Moreover, wireless sensors can even be placed at locations difficult to wired to, offering us more options for data acquisition purpose.

- The low-cost and ease of deployment of WSSN also allows for dense instrumentation which facilitates improved condition evaluation and damage detection of complex and large civil infrastructures. Because buildings and bridges are typically large and complex, information from just a few sensors is inadequate to accurately assess there structural condition, moreover, damage/deteriation is intrinsically a local phenomenon. Therefore, to comprehend the dynamic behavior and structural condition of possibly locally damaged structures, spatially dense implementation of sensors are usually necessary. This requirement can be hardly met by traditional monitoring systems but easily met by a WSSN monitoring system.

- The on-board computational power of smart sensor nodes supports fully autonomous and distributed operations. Equipped with on-board CPU, wireless smart sensor can locally process data and only transmit important information, reducing communication burden and the amount of raw data generated by traditional monitoring systems. Moreover, as a network formed by such smart sensors, WSSN can be fully autonomous and perform various kinds of monitoring tasks. For example, by performing data analysis, smart sensor unit is capable of detecting earthquakes itself and enabling a fully autonomous seismic response monitoring system for civil infrastructure.

## 1.2 WSSN seismic response monitoring system

Though WSSN has been used by a number of researchers in the filed of Structural Health Monitoring(SHM), no WSSN monitoring system has been developed for the purpose of autonomous monitoring for seismic response of civil infrastructure. Since earthquake response is a global short-term transient event that requires all implemented sensor nodes to be continuously sensing for over a long period, it defies most of the previously developed WSSN applications that only perform short-term structural health monitoring and damage detection, neither does it conform to the autonomous SHM application reported by JA Rice(8) that only keeps awake several sentry nodes for event detection, this special requirement poses challenges for the stable long-term performance of WSSN system as well as the limited power and memory resource on each wireless sensor nodes. These challenges are explained in details below:

- A stable long-term event detection method is demanded to make the WSSN seismic response monitoring system autonomous and prevent false records. Since the WSSN seismic response monitoring system has to continuously run for a long-term in order to capture one possible earthquake. An event detection method should be developed to efficiently use the limited memory resource on wireless sensors. Meanwhile, the stability of this event detection algorithm is also essential for detecting the abnormal vibration of earthquake response and prevent false alerts during a long sensing period.

- Accurate long term synchronization should be guaranteed over the entire network for the recorded seismic response to be meaningful. Each sensor node in the WSSN network maintains a local clock and stamps the stored seismic response data according to the readings of this clock. Difference of local clock readings between different sensor nodes yields time-shifted signals, these time-shifted signal will cause phase-shifted modes, and possibly falsely indicate structural damage. Thus, the local clocks of all the sensor nodes in the WSSN must be kept synchronized throughout the sensing period.

- Long-term stable power supply is another challenge for WSSN seismic response monitoring systems. Both sensing and radio communication are power-consuming operations. Therefore, in order to keep the sensors sensing and communicating for a long period, each sensor node should have long-termly stable power supply.
- Last but not least, an efficient multi-hop data collection strategy is needed to retrieve data from the entire WSSN in a prompt manner after seismic events for safety concerns. Since a WSSN seismic monitoring system will be distributed on the entire civil infrastructure, multi-hop communication is necessary for the functionality of the network. Efficient multi-hop data collection from the entire WSSN is a challenge that engineers have to face in designing such a WSSN seismic response monitoring system.

These challenges have hindered the application of WSSN in the field of seismic response monitoring.

## 1.3 Research Scope and Limitations

This research mainly attempts to address the challenges described in Section.1.2 and develop such a stable long-term autonomous monitoring system for the seismic response of civil infrastructures using Wireless Smart Sensor Network(WSSN). Meanwhile, this developed monitoring system should be flexible and easy to be adopted in a more general range of applications of monitoring civil infrastructures' response under various transient dynamic events.

### 1.3.1 Research Objectives

The objectives of this research are four-folds:

1. Develop a wireless monitoring system for general random transient events, which can be applied to monitor the dynamic response of civil infrastructures under a wide range of transient events, for example, traffic loads, strong wind load as well as earthquakes.
2. Program modification for long-term applicability: towards the monitoring for seismic response of civil infrastructures.
3. Develop an efficient multi-hop service for static wireless sensor networks.
4. Experimental validation of the developed program.

### 1.3.2 Thesis Structure

This thesis is divided into seven chapters, each of them focus on a separate topic. An outline is given as follows:

Chapter 1: Introduction. A brief introduction of Dynamic Events Monitoring, Seismic Response Monitoring and Wireless Smart Sensor Network is given. Research objectives, thesis structure and research limitations are explained.

Chapter 2: Background. The hardware and foundation software used in this research are introduced. The hardware used in this research involve Imote2 smart sensor platform, SHM-A accelerometer and accessory antennas. The software foundation for this research is the open-source service toolsuite provided by the Illinois

Structural Health Monitoring Project(ISHMP).

Chapter 3: Data acquisition for general dynamic events monitoring of civil infrastructure. The data acquisition module developed for general random transient events is presented. An event detection method that can be used to quickly and stably detect abnormal vibration on wireless smart sensor platforms is developed and implemented. Application examples are also given and explained.

Chapter 4: Long-term applicability: towards seismic response monitoring. In this chapter, the issues of long-term power supply and long-term time synchronization are addressed. Extensions for seismic response monitoring are made. And the time synchronization performance is evaluated.

Chapter 5: Efficient multi-hop service for static wireless sensor networks. The efficient multi-hop communication service for the dynamic event monitoring system developed in this research is proposed, explained and evaluated in details.

Chapter 6: Experimental Applications. The developed system is further applied to two examples to evaluate its performance in full scale applications. On Campus Test and Rainbow Bridge Measurement. The results from these experiments are presented and the potential problems of the developed system are identified.

Chapter 7: Conclusions and future work. Research conclusions and suggestions for future work are summarized.

### 1.3.3 Research Limitations

The development in this research are mainly software-wise. Hardware instabilities, such as sensor data spikes, Flash write failure and ect., have been observed during the development of the proposed monitoring system. Some of these issues are addressed in Chapter 3 and 4, others are left unaddressed. These hardware instabilities happen infrequently, but they need our treatments in the future for realistic long-term implementations of the developed system. Also, for long-term power supply, the purposed system resorts to the exterior power supply, this is a straight violation of the wireless concept, however, as will be explained in Chapter 4, this compromise of wirelessness will not severely offset the advantages of WSSN but rather be necessary for long-term implementation and seismic response monitoring. The other limitations associated with multi-hop service will be explained in Chapter 5 and Chapter 6.

# Chapter 2

# Background

As the forming units of WSSN monitoring systems, wireless smart sensor nodes are the cornerstones of the proposed dynamic event monitoring system. A wireless smart sensor units is composed of a reliable sensor board that can provide high-fidelity acceleration data, a smart sensor platform that has on-board computational power to locally interpret the data, wireless communication radios and sufficient on-board memory to store the response records and suitable software drivers to control the hardware components of the sensor units. In this research,Imote2 smart sensor platform, SHM-A sensor board and and open-source toolsuite provided by Illinois Structural Health Monitoring Project(ISHMP) are chosen as the basic components of a wireless smart sensor unit.

## 2.1 Imote2 smart sensor platform

The smart sensor platform used in this research is the Imote2 smart sensor platform developed by Crossbow Technology. Inc., as shown in Fig.2.1. It is an advanced wireless sensor node platform built around the low-power PXA271 XScale CPU and CC2420 IEEE 802.15.4 radio transceiver. The design is modular and stackable with interface connectors for expansion boards on both top and bottom sides. The integrated CPU allows for Imote2 to perform onboard computation and enables

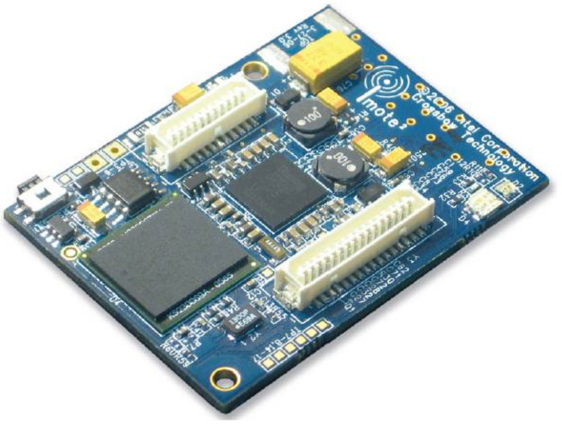

Figure 2.1: Imote2 smart sensor platform

autonomous distributed data processing of the wireless sensor network. In the developed seismic monitoring system of this research, it serves as the foundation of the seismic event detection algorithm. Meanwhile, the CC2420 radio provided by Imote2 supports a 250kb/s data rate with 16 channels in the 2.4GHz band, empowering an efficient multi-channel multi-hop data collection strategy. Moreover, the onboard memory of Imote2 constitutes another important feature that sets it apart from other available platforms, it has 256KB of integrated SRAM, 32MB of external SDRAM and 32MB of flash memory. The memory resource is sufficient for many complex SHM algorithms and the need to record tens of minutes worth of data. The detailed hardware reference manual can be found in (9).

## 2.2 SHM-A sensor board

SHM-A sensor board is specifically designed to interface with Imote2 smart sensor platform as part of the Illinois Structural Health Monitoring Project. This versatile sensor board is tailored to Structural Health Monitoring(SHM) applications and is capable of providing the information required for comprehensive infrastructure monitoring. Basically, SHM-A has three axis of acceleration measurement and user-selectable sampling rate accommodating the needs of a wide range of vibration-based SHM applications as well as seismic monitoring purpose. The key onboard

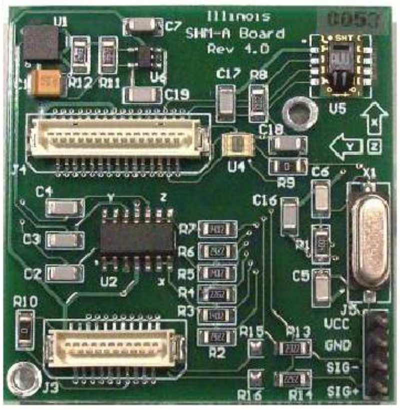

Figure 2.2: SHM-A sensor board

component Quickfilter QF4A512 ADC and signal conditioner provide a versatile 16-bit resolution ADC, reliable anti-aliasing and digital filters. A software driver for the SHM-A board has also been developed in TinyOS system to control the functions of QF4A512. After initializing the onboard ADC and triggering the sampling, the driver releases sampled data as two-byte signed integers(16-bit) from the sensor board to the Imote2 buffers. The data can then be further used for variable applications running on the Imote2's processor(8). A top view of SHM-A sensor board is given in Fig.2.2

## 2.3 ISHMP service toolsuite

Programming smart sensor is a complex task that includes algorithm implementation and network functionality. This difficulty has partially hindered the development of WSSN technology for monitoring of civil infrastructures. Service-oriented architecture(SOA) has been proposed as a way to tackle the complexity associated with dynamic and heterogenous distributed applications(10)(11). It is also suitable to address the challenges of designing dynamic WSSN applications. A typical application built using SOA consists of a number of linked services within a middleware runtime system that provides communication and coordination between them. Data is passed among the services in a common format and the services do not require knowledge of its origin. Different applications can be built from the same set of services, depending on how they are linked and executed(12). ISHMP service toolsuite is an open-source WSSN software framework based on the design principles of SOA. It provides foundation services that consist of the building blocks of the other higher level applications, application services that perform different SHM algorithms as well as tools to test and adjust the WSSN application to specific monitoring objects(8). The seismic response monitoring system developed in this research is mainly built on the foundation services provided by ISHMP toolsuite with suitable customizations. The UnifiedSensing service is used to continuously acquire data from the sensor board, the TimeSync service is specifically customized to perform accurate long-term synchronization, and the ReliableComm service is employed for reliable hop-by-hop data transport used in the developed multi-hop data collection protocol. The software structure is given in Fig.2.3.

The white blocks are the original foundation services provided by ISHMP service toolsuite, while the gray blocks are developed application components involved in the dynamic event monitoring system. As explained earlier, the developed system consists of three basic modules: a data acquisition module, a long-term time synchronization module and a multi-hop service module. Each of these modules have their own respective functionality and program design. Detailed explanation of these modules will be presented in the following chapters.

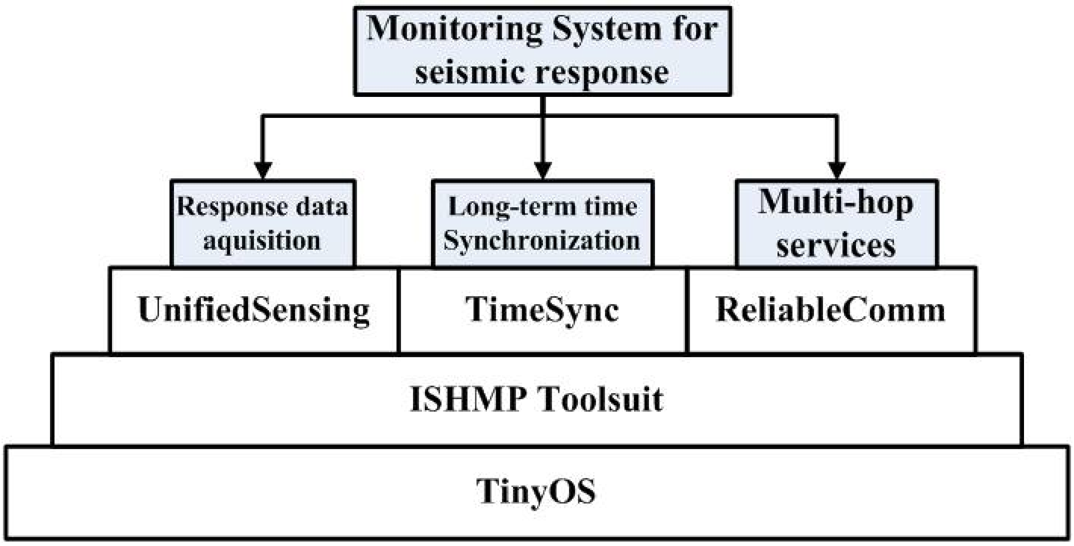

Figure 2.3: Software structure

# Chapter 3

# Data acquisition for general dynamic events monitoring of civil infrastructure

One of the key components of the developed dynamic event monitoring system is the data acquisition module for general random transient events. For example, when earthquake happens, the WSSN distributed on the civil infrastructure should be able to capture the entire response history of the infrastructure. For traditional monitoring systems, data from individual sensors is continuously sampled, sent back and stored at the center station. However, for a wireless monitoring system, this flow of application is no longer applicable due to the limited resources of wireless sensor node. The communication speed of wireless sensor node is too slow to send data back real-time to a center station for storing and analysis, while the on-board memory of the sensor nodes itself should be used as an alternative for data storage. Moreover, to efficiently use the limited on-board memory, only data of interest should be stored, this in turn requires us to development an event detection method which is compatible with the limited computational power of Imote2 platform and can quickly and stably detect abnormal vibration response of civil infrastructure under earthquakes. Therefore, this chapter is dedicated to develop such a data acquisition system with proper event detection method that is suitable for general random transient events. These events under consideration range from vehicle-induced response to earthquake induced vibration of bridges.

## 3.1 A monitoring system for general random transient events

A complete flow of the data acquisition process is outlined in Fig.3.1. The sensor nodes are divided into three groups, ie. gateway-node that sends command to the network and performs data retrieving, head-nodes to detect abnormal response of civil infrastructures under transient events and leaf-nodes densely placed on the infrastructures to capture the entire response history. Both head-nodes and leaf-nodes are continuously running after sensing starts, the sensed data sets are temporarily stored into a 30-second-long buffer by the Imote2 processor, the buffer is constantly being overwritten in order to keep the most recent input. Meanwhile, head-nodes are simultaneously checking each data samples passed from the sensor board. Once abnormal vibration is detected on the head-nodes, an alert is signaled by the head-nodes and travels through the entire network in a flooding manner, upon receiving the alert, leaf-nodes store the buffered data into flash memory and also start storing data samples for the next user specified period. In this way, the complete response under a random transient event can be recorded by the WSSN monitoring system. Afterwards, engineers can use the gateway-node to retrieve the data stored on the leaf-nodes and use the records for various kind of analysis.

### A quick and stable event detection method

As mentioned above, wireless sensor nodes have limited onboard memory resource, while successful recording of seismic response requires all the sensor nodes to continuously perform sensing for a long period. Storing all the sensed data is both

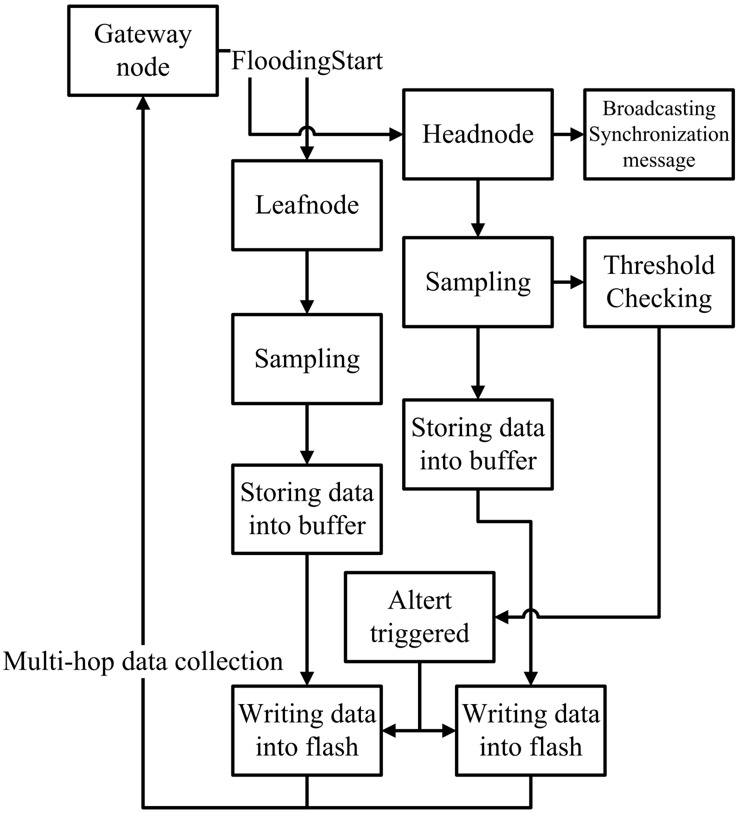

Figure 3.1: Data acquisition for general transient events

impossible and unnecessary. Also, earthquake happens in a short-term transient manner, it demands the quick reaction of the network to capture the complete seismic response of civil infrastructures. Thus, a quick and stable method on the head-nodes to detect abnormal vibration and subsequently trigger the storing of the leaf-nodes is the first task to accomplish. This method is also required to be as simple as possible in order to be compatible with the limited online computational power of the smart sensor platform and to run real-time with the continuous sensing of the sensor board. Bearing these requirements, amplitude check naturally comes into mind. The 16-bit ADC-valued data(sample) sampled from the environment and generated by the SHM-A sensor board takes the following transformation to the actual physical acceleration.

$$\text{sample} = \text{SCALE} \times \text{acceleration} + \text{OFFSET}$$

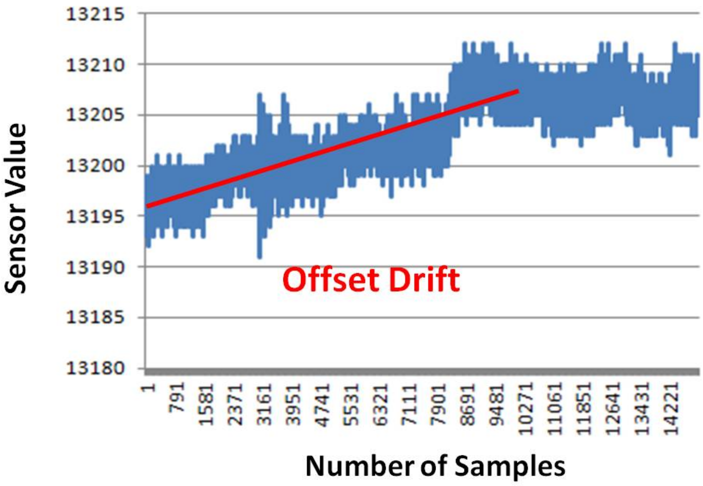

Figure 3.2: An example of OFFSET drift

Set a threshold for the acceleration and performs amplitude check for each data sample from each channel could be a quick detection of abnormally large vibration. However, issues have to be considered before we can cast it into a practical and stable method. These difficulties and their respective solutions are explained in details:

First, both SCALE and OFFSET in the above equation are dependent on different sensor nodes and varies from channel to channel, exact knowledge of these values can only be achieved through rigorous calibration test. However, just for the threshold checking purpose, exact values would be extravagant and unnecessary. Moreover, the OFFSET is also time dependent, large drift of the OFFSET value has been reported(8) and observed by the author. An example of OFFSET drift is given in Fig.3.2. This drift is due to the board temperature change caused by the environmental conditions as well as the heat generated by the sensor node itself. Since this drift can potentially compromise the threshold judging, trigger false alert and jeopardize the stability of the event detection, an initialize-and-update strategy is used to automatically compute the OFFSET and keep it updated. In the developed data acquisition program, the mean value of the first ten seconds of data right after the sensing start is utilized as the initial value of OFFSET, and this value is also constantly updated by the fresh normal samples every three sec-

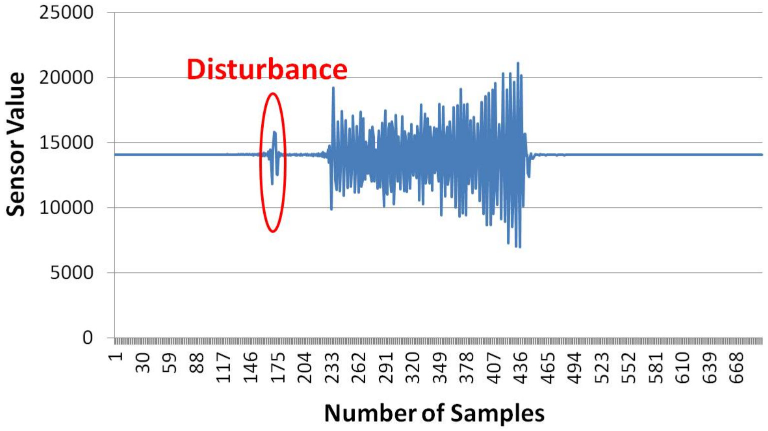

Figure 3.3: An example of disturbance

onds throughout the sensing process. Using this initialize-and-update strategy, not only sensor and channel dependent OFFSET value can be easily and automatically computed, but also the OFFSET drift can be properly considered in the threshold checking process, making the event detection more stable in a long-term.

Second, the second difficulty comes from disturbance(Fig.3.3) and sensor value spikes(Fig.3.4). Either a minor human disturbance or a undesirable sensor value spike(which is quite frequently observed by the author during program development) can cause a pulse like abnormal signal for the head-nodes and trigger the data storing of the network, this consumes both unnecessary energy and memory resource of the sensor node, and it may even cause flash memory overflow that makes the entire monitoring system to fail. Therefore, the desired detection algorithm should be able to ignore these unwanted events and not signal false alert in such cases. To do this, several counters are kept in addition to the buffered data as a constantly updated simple statistics of the current signal status on the head-nodes. An alert is only triggered if out of any ten second period five seconds worth of data surpass the threshold. These values are highly empirical, but they should be set long enough to eliminate the unwanted events and not too long to impair the timely response to the real events of interest. Meanwhile, as can be observed in Fig.3.4, the spike of sensor value is characterized by an isolated sudden and steep change of the sample

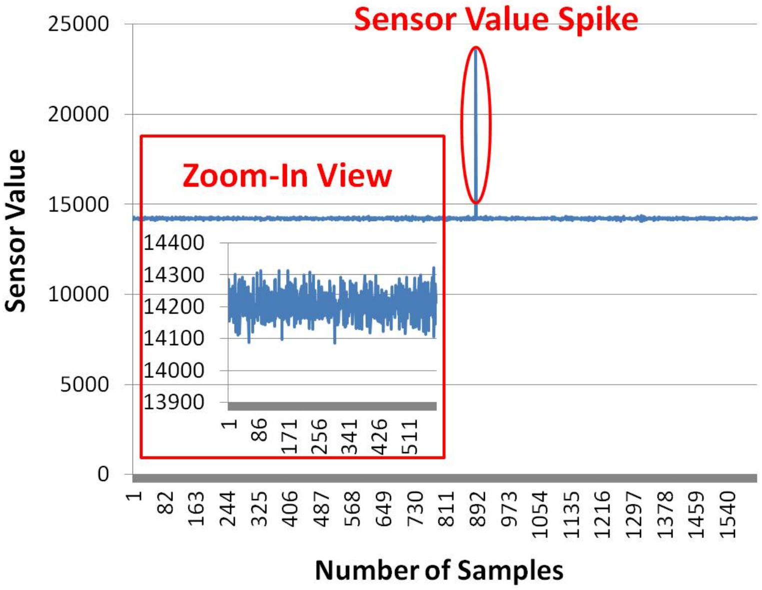

Figure 3.4: An example of sensor value spike

reading while normal vibration records are always gradually increasing or decreasing in amplitude. By comparing the data records in one second, spikes can be easily separated from normal data readings.

Third, unlike the gradual drift of OFFSET in the above explanations, a sudden change of OFFSET could be caused by sensor dislocation induced by earthquakes or accidents, as shown in Fig.3.5. This difficulty can not be handled like the OFFSET drift since once it happens, no vibration sample will be judged as normal by the head-node again, thus OFFSET update will also be terminated. Therefore, the event detection algorithm requires a self-healing ability to automatically correct the sudden changed OFFSET value and balance the threshold checking to normal state. For this purpose, a timeout period for continuous data storing is defined, if this timeout period, for example 3 minutes for earthquakes, is passed, but the head-node is still judging data samples as abnormal, an automatic correction is triggered to set the OFFSET value back to the most recent sample again. With this self-healing ability, the event detection method is capable of compensating for any sudden change of sensor position or any other unexpected behavior of sensor

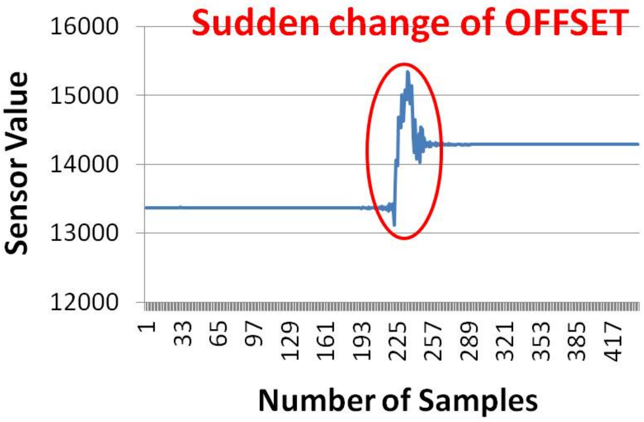

Figure 3.5: An example of sudden change of OFFSET

OFFSET value.

## 3.2 Application example

The described data acquisition program has been implemented on the Imote2 smart sensor platform and tested both on shaking table in the laboratory and real measurements. Examples are given in this section to show the applicability of the proposed event detection method.

The first example is from a shaking table test, one head-node and three leaf-nodes were placed on a shaking table, and the shaking table were given a series of vibrations with different frequencies. Fig.3.6 shows the time history record from one leaf-node sampling at 100HZ, each vibration period of the shaking table were successfully captured by the network.

The second example was conducted on a steel bridge on JR Senzan-line between Sendai and Yamagata. The bridge is shown in Fig.3.7. The purpose of measurement is to record the train induced vibration of the bridge, and compare the bridge response before and after repair. Eight wireless sensor nodes including two head-nodes were instrumented on the girder and piers of first span of the bridge. The

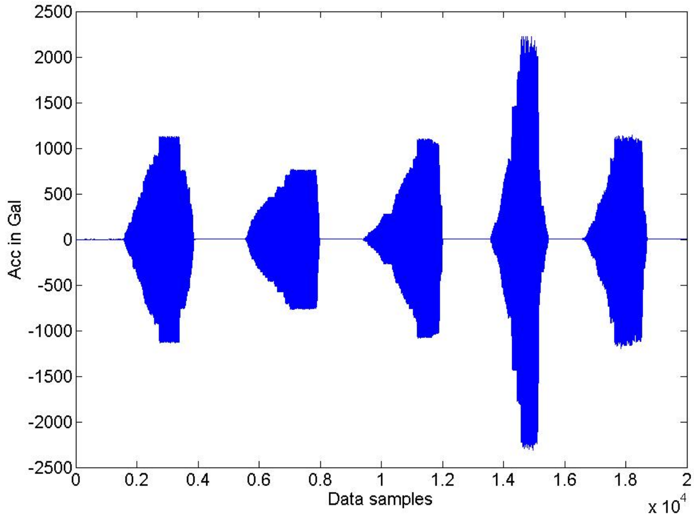

Figure 3.6: Shaking table test

Figure 3.7: Measurement 1

two head-nodes were placed on the girder mid-span where vibration amplitude is supposed to be the largest. When train is on the bridge, large vibration set off the alert on the head-nodes and triggered the data storing of all the other leaf-nodes. Fig.3.8 shows part of the measurement results from a leaf-node for three successive train passes. As can be clearly distinguished from the recorded time history, three train passes were all successfully captured by the WSSN monitoring system.

The third example was conducted on a highway bridge in Shibuya, Tokyo. The

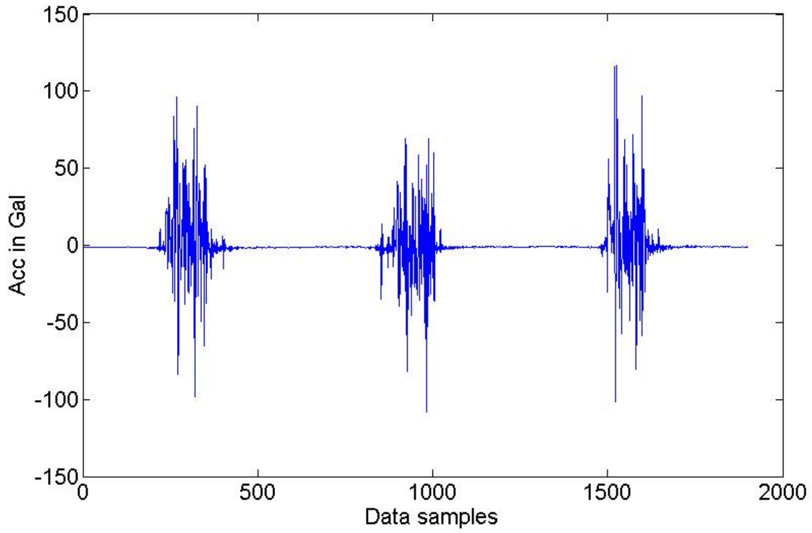

Figure 3.8: Time history of train induced vibration

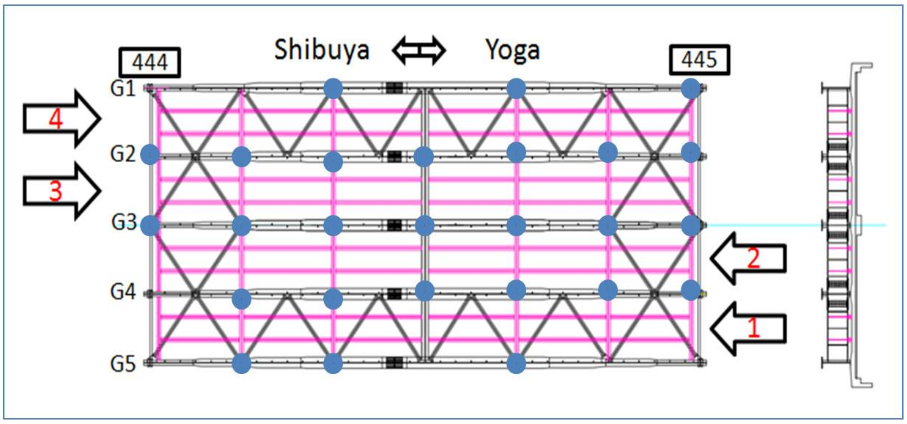

Figure 3.9: Measurement 2

purpose of measurement is to record the truck induced vibration of the bridge and perform modal analysis. Two head-nodes and twenty-six leaf-nodes were used and distributed on the girders of the bridge, as shown in Fig.3.9. Since the bridge was not closed during the measurement, it was difficult to separate the truck of interest and other running vehicles, therefore, setting a high threshold and manually shaking the head-node when the truck of interest was on the bridge was adopted as the event detection method. A typical time history record from one leaf-node is shown in Fig.3.10. This record includes four events, they are difficult to distinguish because even when the truck of interest was away from the bridge, other vehicles were still running on the bridge. However, the time-stamps for data samples can be

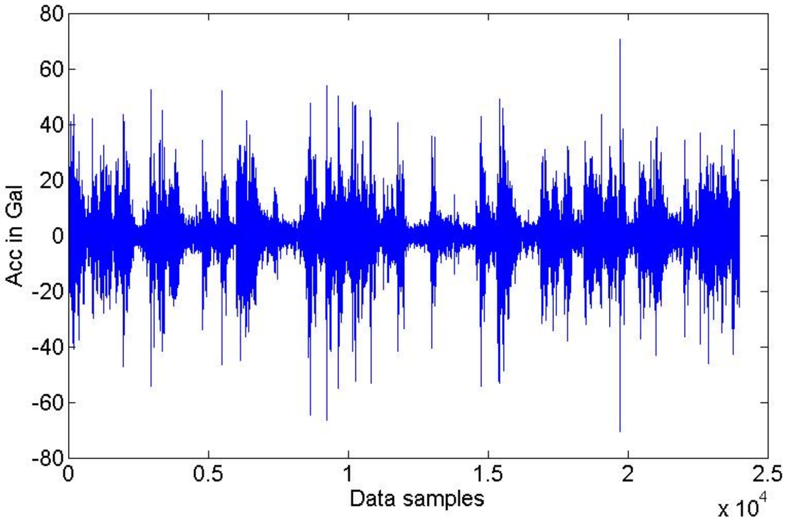

Figure 3.10: Vehicle induced vibration of bridge

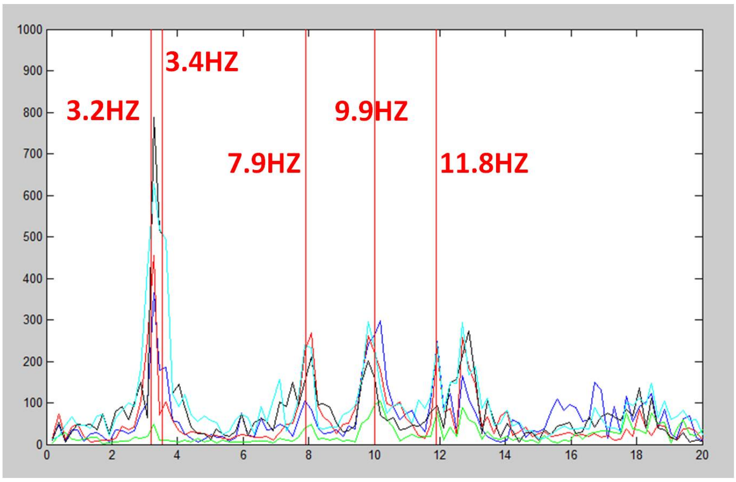

Figure 3.11: Vehicle induced vibration of bridge: frequency domain

used to distinguish each truck-passing events. Fig.3.11 shows the frequency domain representation of the bridge free response after truck leaving, the free response can be further used for modal analysis.

By using the records of sensor nodes from a number of selected positions, the first five modes of the highway bridge are identified using ERA method and shown in Fig.3.12 to Fig.3.16.

From all the examples above, it is valid to conclude that the developed data ac-

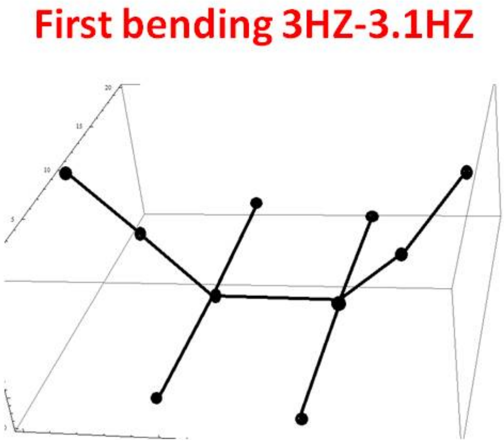
First bending 3HZ-3.1HZ

Figure 3.12: First mode

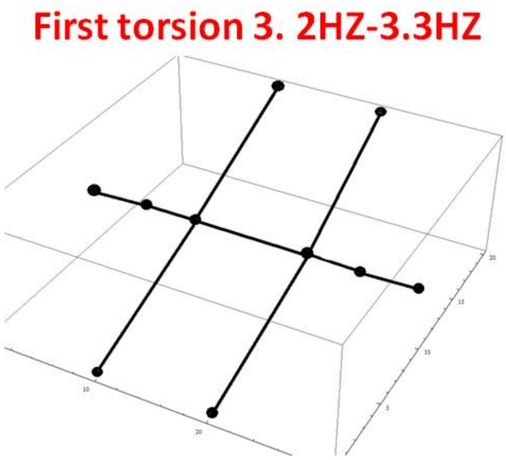
First torsion 3. 2HZ-3.3HZ

Figure 3.13: Second mode

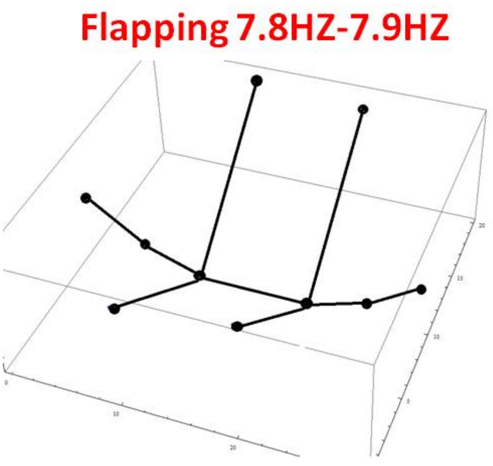
Flapping 7.8HZ-7.9HZ

Figure 3.14: Third mode

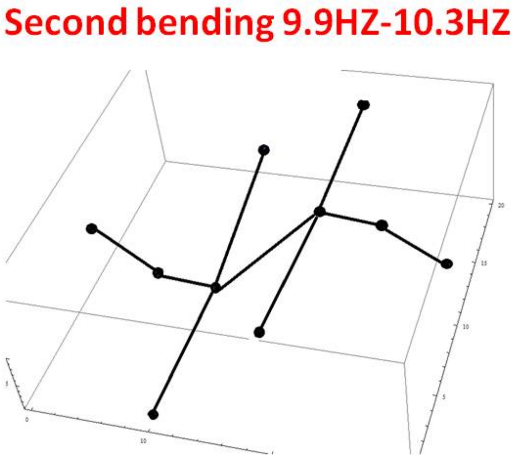

Figure 3.15: Fourth mode

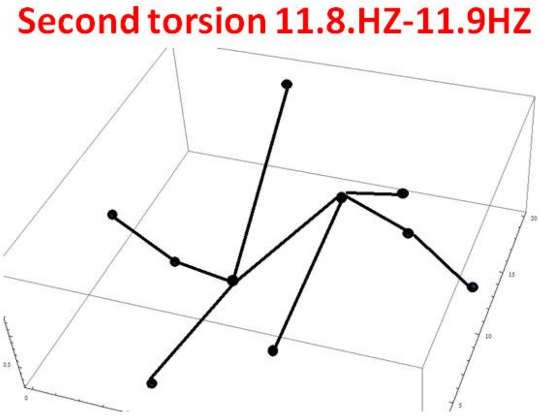

Figure 3.16: Fifth mode

quisition system for general dynamic events monitoring are effectively implemented and can be used for various kinds of monitoring purposes.

## 3.3 Conclusion

In this chapter, a quick and stable event detection method is developed for the monitoring of general dynamic events of civil infrastructure. The method is implemented on Imote2 smart sensor platform and tested in various experiments and measurements. The efficacy of the proposed method is demonstrated by three application examples.

# Chapter 4

# Long-term applicability: towards seismic response monitoring

From the short-term monitoring of dynamic events of civil infrastructures to the long-term seismic response monitoring, the developed system requires essential extensions for long-term applicability. As explained in Chapter 1, the challenges of such long-term seismic response monitoring mainly come from stable power supply and accurate long-term time synchronization. Therefore, this chapter is dedicated to face these challenges and make the developed system long-term applicable for the purpose of seismic response monitoring.

As discussed before, monitoring the seismic response of civil infrastructures demands the WSSN to continuously run a long period. This is a big challenge for the limited resources of wireless sensor nodes. Chapter 3 has already dealt with the limited onboard memory resource by letting the WSSN monitoring system only record the events of interest. That is, although the sensors are sensing all the time, they only record the seismic response of the infrastructure which triggers the event detection method on the head-nodes. However, the limited power resource is still left as a challenge. Without a long-termly stable power supply, WSSN monitoring systems can hardly perform such power-intensive seismic response monitoring tasks. Meanwhile, the random and transient feature of earthquake also demands the WSSN to be readily synchronized at any moment throughout the sensing period. A long-term accurate time synchronization method is thus needed to keep the local clocks of all the sensor nodes in WSSN in keeping with one another, so that once earthquake happens, all the sensors can provide consistent time records of the stored seismic response.

## 4.1 Long-term stable power supply

Fully wireless sensors run on batteries, the limited power resource does not support a long-term implementation of wireless seismic response monitoring system that requires sensors always keep sensing and radio active to receive and broadcast synchronization packets. Although research of developing advanced power harvesting systems on node level provides a promising choice(13)(14)(15)(16) for long-term power supply, most of these systems are either immature or too costly for general installation, further more, the available energy source is too small to support the so power-intensive seismic response monitoring. A change of mind can lead to an alternative solution, that is, we can source to the existing power outlets which are readily available in common civil infrastructures. Since buildings are usually equipped with power outlets, and many bridges also have power that is used for road lights, having access to these existing power sources is not a difficult task. Also, since the cabling for power supply is considerably easier than that for data communication, and once installed the sensor nodes will be stationary for a quite long period, this little compromise of wirelessness does not significantly offset the merits provided by the WSSN and meanwhile enables more power-intensive monitoring applications like the seismic response monitoring. This tradeoff is considered necessary for successful implementation of wireless seismic response monitoring system under current conditions.

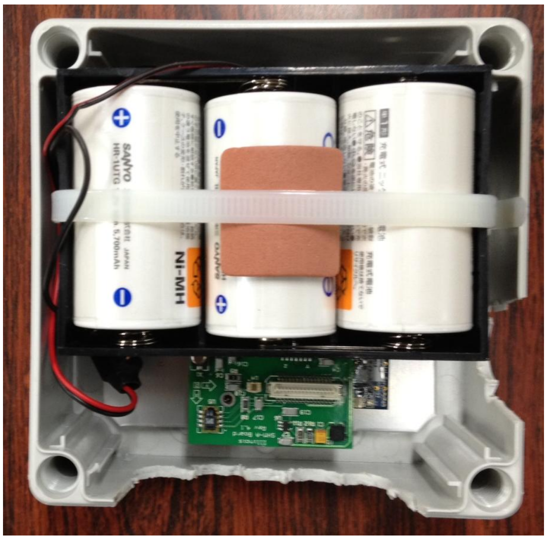

Figure 4.1: Backup batteries

Following this train of thought, we have designed a portable sensor box that has battery carrier as well as an interface to general AC power source. As shown in Fig.4.1 and Fig.4.2. Under normal conditions, power will be supplied through the AC power cable connecting to the existing power system of common civil infrastructures. And the backup batteries are supplemented to make sure the WSSN system will not stop even during the possible blackout emergencies. Meanwhile, the battery carrier has a dual function as a battery charger, when the power is supplied to the sensor through the power cable, backup batteries are being charged simultaneously, this design further makes the power system renewable and enhances the long-term stability of the entire system.

This power system has been tested in a ten-day continuous running of four sensor nodes. Manual switch between battery power and AC power were conducted multiple times. The backup batteries are enough to support the sensor node running for over 20 hours, which is a sufficiently long period to cover most possible emergent blackouts. This portable sensor box is shown to be able to provide long-termly stable power supply for the developed WSSN monitoring system, and to make the realization of power-intensive seismic response monitoring possible.

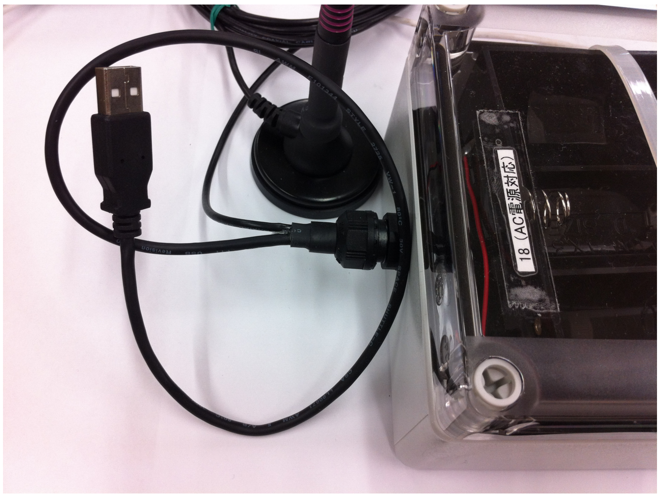

Figure 4.2: AC power interface

## 4.2 Long-term time synchronization

Long-term synchronization is another important issue. For the accurate data analysis after earthquakes, each sensor node should have consistent time records of its stored seismic response. Different protocols have been proposed by previous researchers to achieve network-wide time synchronization. Some of them have synchronization accuracy as good as tens of microseconds. However, for civil infrastructures commonly with low natural frequencies below 10HZ, a synchronization accuracy of one millisecond between any pair of sensors would be enough. Therefore, considering the hop-accumulation of time synchronization error, the desired time synchronization accuracy of this research is set to be 0.1 millisecond per hop.

Among all the available time synchronization protocols, Flooding Time Synchronization Protocol(FTSP)(17) is adopted as a prototype in this research. Basically, FTSP attempts to use the MAC-layer time-stamping to eliminate the uncertain error sources in order to achieve high-accuracy time synchronization between message senders and receivers. Also, FTSP achieves its robustness against node failure or topology change by utilizing periodic flooding of synchronization messages and implicit dynamic topology update. The reported average synchronization error falls in

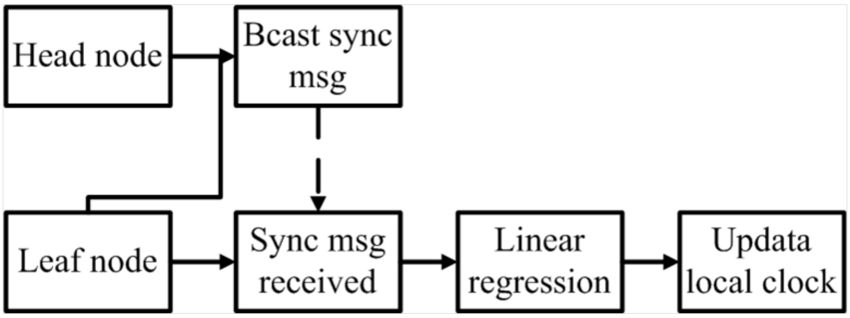

Figure 4.3: Long-term time synchronization

microsecond range per hop. In the developed monitoring system, the network-wide long-term synchronization is achieved and kept in two separate stages. In the first stage before sensing starts, network-wide synchronization with the gateway-node is initially achieved using FTSP. In the second stage during the sensing period, one user-selected head-node serves as the time synchronization reference and performs long-term FTSP time synchronization by periodically flooding clock messages over the network. Meanwhile, to consider the clock drift under long sensing period, a pairwise linear regression model using the latest 20 minutes' time records is also included to compensate the clock speed difference between synchronization pairs. This process is continued until sensing is stopped. In this manner, the network-wide synchronization is initially achieved and constantly kept for the long-term seismic response monitoring purpose, and the developed monitoring system is able to provide consistent time records whenever earthquake happens. A flow of the long-term synchronization is given in Fig.4.3, and the linear regression to evaluate clock skew is demonstrated in Fig.4.4.

To evaluate the long-term synchronization accuracy of the customized FTSP, several experiments were conducted on a shaking table. Sensors were programmed to take different levels in the time synchronization protocol in order to evaluate the error accumulation through different hops, and they are left running continuously for more than one week before vibration is given to the shaking table. The cross-phase spectrum is used to calculate the time synchronization error between two same but

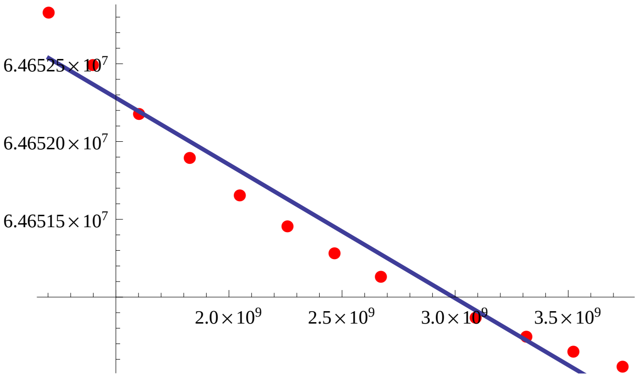

Figure 4.4: Linear regression to evaluate clock skew

time-shifted signals. Since 1 second time shift corresponds to a 360 degree phase shift at 1HZ, time synchronization error between two signals can be easily evaluated by scaling against this standard. The raw vibration records from the sensor nodes were first put through a resampling process to eliminate the start delay. Then the pure synchronization error can be evaluated following the cross-phase method described above. The following Fig.4.5 and Fig.4.6 show one example of the time synchronization experiments. Four nodes at different hops are compared in both time domain and cross-phase spectrum. The synchronization error indicated by the cross-phase spectrum is approximately 0.2 millisecond per hop, suggesting a good time synchronization accuracy is maintained during the long-term sensing. A linear regression to approximate this synchronization error from multiple experiments is illustrated in Fig.4.7.

## 4.3 Conclusion

In this chapter, power and synchronization issues for long-term application of the developed WSSN monitoring system are addressed. Long-termly stable power supply is provided by a specifically designed sensor box supporting both local batteries and exterior AC power source. Long-term time synchronization is achieved by using a customized FTSP in combination with a linear regression model to compensate for clock skew. These extensions ensures the long-term applicability of the developed

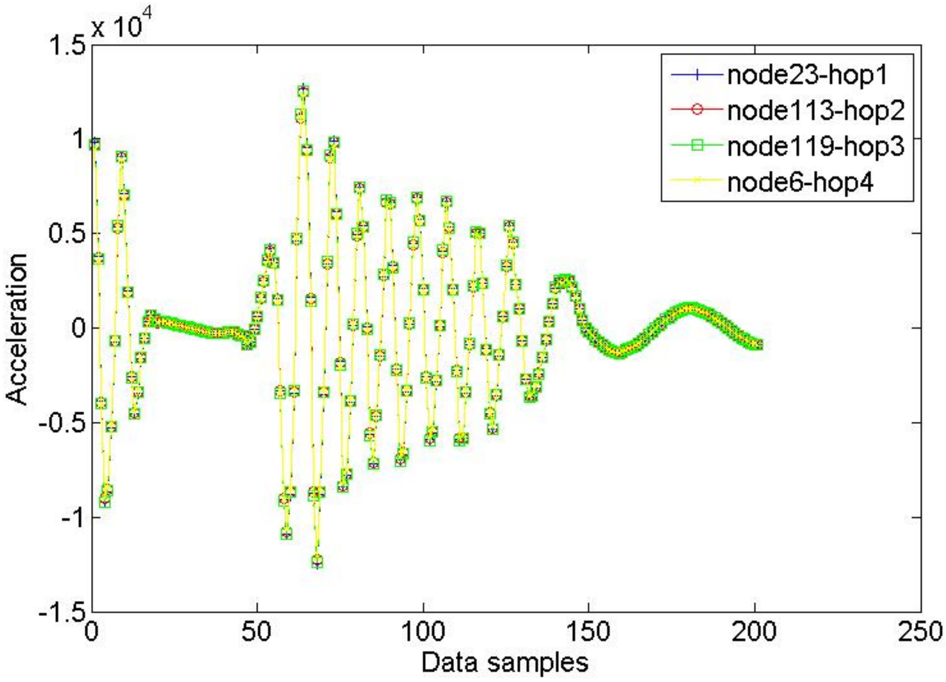

Figure 4.5: Time domain comparison

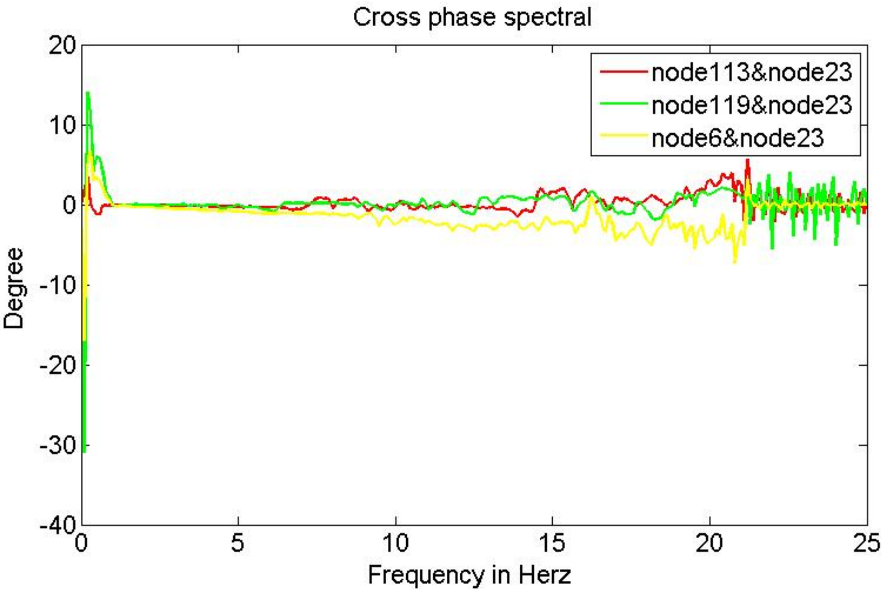

Figure 4.6: Cross-phase spectrum

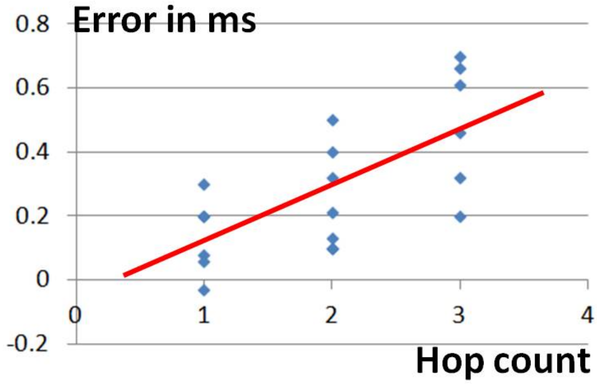

Figure 4.7: Multi-hop time synchronization error

system and make seismic response monitoring of civil infrastructures possible.

# Chapter 5

# Efficient multi-hop service for static wireless sensor networks

Monitoring of dynamic event induced response requires sensors to be thoroughly distributed over a large-sized civil infrastructure. Meanwhile, the radio power of wireless sensor node is usually limited. These conditions disallow direct radio communication between gateway node and all the other sensor nodes as needed, and thus pose difficulty for wireless monitoring systems solely based on single-hop communication patterns. Therefore, a multi-hop service is demanded to realize the desired functionality of the dynamic event monitoring system. Basically, multi-hop communication is comprised of two phases: the routing phase discovers suitable path between source node(s) and destination and the data transport phase uses the established routes to deliver data. Though many multi-hop routing and data transport protocols have been proposed by network engineers(18)(19)(20)(21)(22), they do not necessarily meet the special requirements and utilize the special characteristics of the dynamic event monitoring of civil infrastructures. Nagayama(23) has pointed out the specific communication characteristics of Structural Health Monitoring and attempted to develop reliable multi-hop communication strategies for SHM purpose. Here, similar to SHM, a suitable multi-hop service for dynamic event monitoring(especially seismic response monitoring) should also consider the following special requirements and characteristics: simple and quick demand dissemination, stationary and dense instrumentation of sensors, complex radio communication environment, and prompt and reliable data collection from all sensor nodes after possible seismic events. These requirements and characteristics provide both convenience and challenges for the development of such a suitable multi-hop service. For example, the predetermined and fixed locations of sensor nodes eliminates the need to account for dynamic topology and frequent link quality change, stable static routes is preferred to reduce both communication overhead and network traffic collision. As for the challenges, the complex communication environment on complicated civil systems can cause serious link asymmetry and prevent reliable bidirectional communication, routing protocols thus should adopt a round-trip quality pick for each established link. Meanwhile, safety concerns after such dynamic events(eg. earthquake) put extra emphasis on the promptness of data collecting from the entire network, thus deny the usage of direct reliable end-to-end data transport protocols that only allows a single data flow to sink for each sensor node at any instant(20). Accounting for these requirements and characteristics of dynamic event monitoring, the multi-hop service developed for proposed system includes an efficient command diffusion method, an improved flooding-based single-sink multi-hop routing protocol that is able to generate a stable static routing tree and also a highly efficient globally coordinated data collection strategy upon the pre-established routes.

## 5.1 Multi-hop command dissemination

The command dissemination used in the developed dynamic event monitoring system is a typical flooding based application, the simplicity and efficiency provided by flooding method is highly appreciated for the seismic response monitoring as well as other transient event induced vibration monitoring of civil infrastructures. Message redundancy is eliminated by requiring the sensor nodes only reacts to the first received flooding message, and flooding convergence is guaranteed by integrating a Time-To-Live(TTL) counter in each flooding message broadcasted.

## 5.2 An improved flooding-based routing method for the generation of stable static routes

To find the reliable routes for efficient data collection requires more sophistication than a simple flooding application. In a traditional flooding based routing protocol, nodes choose the source of first message heard as parent. This approach has been shown naive and form convoluted spanning trees and unreliable links at scale(24). The Single-Sink Multi-Hop(SSMH) proposed by Nagayama adopts Ad-hoc On-demand Distance Vector(AODV)(25) as a prototype, imposes Received Signal Strength Indication(RSSI) as a routing metric to assure link quality, and sets the TTL to one to reduce message congestion and search for shortest path to sink. The link asymmetry is automatically considered by exchanging the RREQ and RREP messages. However, in this approach, the routing message is always initiated by leaf-nodes, each round of broadcasting only establishes one layer, for a large number of nodes, this method can be time-consuming. Meanwhile, backward path information is not kept on sensor nodes, higher layer parents do not know their lower layer children, this prevents a backward communication if needed. Also, the threshold imposed on RSSI should be carefully set in case of nodes relatively remote to the others being partitioned and left out.

Inspired by SSMH, an improved flooding based routing method is adopted in the developed dynamic event monitoring system. The main target of this new approach is to efficiently establish stable static routes for all sensor nodes to sink that can be used by the data collection protocol described in the next section. In comparison with SSMH, this method is much more efficient for large sensor networks, it is able to ensure no sensor node is left out as long as the node can receive even the weakest signal from outside, and also is able to establish the shortest paths to sink and bidirectional high-quality links. Meanwhile, backward path information is kept on each parent-nodes in the network for global coordination purpose during the subsequent data collection phase. The proposed routing method includes four distinct round of broadcasting, each round provides an essential function for efficient formation of the desired stable static routing tree. The first round of broadcasting of routing message is initiated by the sink-node, and propagates to the edge of the network in a scheduled flooding manner. Nodes chooses a level upon the first flooding message it receives that has a RSSI larger than threshold. Each node keeps a parent-list of the ID and RSSI of the five strongest signals it received from higher layers, meanwhile, each node also keeps one same-level-node with the strongest RSSI as possible assistant parent that might be needed later. For a node that only received message lower than RSSI threshold, it will not be assigned a level and thus also not distinguish the level of received message while only keep the strongest five signals in the parent-list. Only leveled nodes are eligible to rebroadcast the routing message and create further lower layers. This process is conducted for several times to ensure the network is fully saturated and each node has reasonable picks in its parent-list. The second round of broadcasting requires each node broadcast its parent-list in a scheduled manner, upon receiving a parent-list, a node will check if itself is included and thus can decide to add the broadcasting node to its child-list, backward RSSI is also recorded in this step to account for possible link quality asymmetry. The third round of broadcasting is conducted by the children possessing parents. Upon overhearing the child-list broadcasted by these parent nodes, a node will confirm the message source is indeed included in its own parent-list and thus can renew the parent-list using the new RSSI and the backward RSSI included. The link quality is determined by the weakest RSSI in the round-trip. For those nodes originally included parent-list but not responding in this round, child node will eliminate them from final selection list. If all the nodes in the original parent-list are eliminated in this round, the assistant parent from the same layer will be activated. Last round broadcasting requires each node picks the most reliable parent from their final selection list and notify the selected parent and adjust its level accordingly. This method leverages on the efficient shortest path generation induced by flooding method and a bidirectional link quality pick provided by the round-trip message exchange. And each link established by this method has been used for at least two round-trip communication trails in the routing process and thus is considered stable. Moreover, a scheduled multiple broadcasting technic is used to make the proposed method work effectively, in each round, all nodes' broadcasting are scheduled according to the nodes' level and ID and conducted multiple times, thus message collision between different levels and different nodes can be reduced to minimum and successful transmission of routing packets can be guaranteed.

## 5.3 A globally coordinated pull-based data collection protocol

Prompt and reliable data collection from all sensor nodes is vital for the dynamic event monitoring of civil infrastructures, and it is even more important for the purpose of seismic response monitoring. Major earthquake is not a frequent event, thus the valuable data recorded on the system should be reliably transferred to engineers for post-analysis. Meanwhile, data collection needs to be done as soon as possible to address safety concerns. This globally coordinated pull-based data collection strategy described in this section accommodates these needs by using the stable static spanning tree created by the foregoing routing protocol.

Typically, a multi-hop data transport strategy has to address three challenges: lossy link, inter-path interference and intra-path interference(20). Thus a multi-hop communication that do not employ coordinated transmission control usually require long data collection time due to packet loss and interference. Such approaches are impractical for applications requiring efficient data collection. To avoid the intra-path interference between different layers, Nagayama(23) proposed a frequency slot division method by using multiple RF channels provided by the CC2420 radio of Imote2. Static channel allocation for each layer is considered a simple as well as stable choice in the proposed SSMH communication. Meanwhile, a single-hop reliable communication middleware service(7) is utilized for hop-by-hop data transport. This single-hop reliable communication protocol provides fast communication and packet loss compensation with only a small number of acknowledgement packets, and thus it is very suitable for efficient and reliable hop-by-hop data transport. The reported data collection rate of SSMH is much higher than an earlier reported MintRoute-based data collection strategy. However, two obvious problems are still left unaddressed. First, the data transport is initiated by the individual leaf-nodes thus lacks a network-wide coordination, the different RF channels between different layers can effectively reduce the intra-path interference, but if multiple nodes in the same layer try to communicate with their parents at the same time, channel contention cannot be avoided, this also slows down the data transport by setting the competing nodes to wait. Second, each node does not know the data collecting progress of the network, they always stay awake until the sink-node signals the entire network to stop using a multi-channel flooding command. A single node failure can prolong the active time of the entire network. This lack of automatic convergence also makes SSMH consume both extra time and power. Despite these existing problems, the idea of multi-channel allocation in combination with the reliable hop-by-hop data transport still breaks a new ground for the development of potentially more desirable and efficient data collection protocols. This idea also constitutes a key feature of the proposed method described later.

The foregoing routing phase is able to generate a stable static routing tree connecting all the leaf-nodes to sink-node through single-hop or multi-hop paths. The subsequent data transport phase utilizes this routing tree and collects all the data bulks from all the sensors in the network. The data transport phase of the developed dynamic event monitoring system is based on a globally coordinated pull-based data collection protocol, which can be theoretically proved able to reduce any kind of channel contention and achieve upmost efficiency for data collection from the entire sensor network. This proposed method inherits the static multi-channel allocation for different layers as well as the reliable communication for hop-by-hop data transport. Also, under the circumstances of no data contention and no topology change, hop-by-hop reliability strongly implies end-to-end reliability, providing another advantage of this method. The data retrieving of this method is always initiated by the sink node(level 0), it attempts to pull data from a selected child node(level 1) with the largest node-branch one node at a time until all data bulks stored in the routing tree are collected. The selection of the largest branch child will exclude the previously pulled child, guaranteeing no child node is consecutively pulled twice unless no other child-nodes are active. This selection mechanism allows essential time interval for the previously pulled child-node to pull data from its own child and prepare to be pulled by the sink-node again for the next time. This interval is also necessary when only one child-node is active for the sink-node, in such cases, the sink-node will wait a certain period before pulling data again from this only child. While the intermediate nodes, once passing their data bulks on hold to their parent-nodes through the reliable single-hop communication service upon requirement, will immediately switch to a higher radio channel and pull data from their next active child-node in a one-by-one scanning manner. Each passed data bulk from any node in the routing tree is attached with a note informing its receiver whether this bulk is the last bulk from the sender itself. For the bottom-level nodes without child-nodes, their own stored data bulks are the last bulks to pass to their parents. Upon confirming a data bulk is the last bulk from a child-node, a parent-node will eliminate the child from its active child-list and will skip this child-node in the next round of data pulling. Also, upon passing the last data bulk to its parent, a node will automatically reset itself and disconnect from the routing tree. In this systematic approach, the spanning tree of the multi-hop routes will gradually shrink and eventually converge, and no channel contention occurs given that only one node in each layer is communicating at any moment and different layers use different radio channels. As will be demonstrated later, the biggest advantage of this method lies in the global coordination provided by the sink node, this coordination not only assures the complete elimination of channel contention but also provides the most efficient order of data transports within the entire network.

The first three steps of the data collection procedure are illustrated in Fig.5.1, Fig.5.2 and Fig.5.3 respectively. Node 0 is the sink-node while a spanning tree has been created by the foregoing routing method. Fig.5.1 shows the start of the data collecting process, node 0 is taking the first data retrieving operation on node 5, which is the first-layer-node with the largest node-branch. After getting data form node 5, as shown in Fig.5.2, node 0 takes the second operation to pull data from node 11, which again is the first-layer-node with the largest node-branch except for the previously pulled node 5, meanwhile, node 5 is requiring data from its first child-node 1 and preparing to be pulled by the sink-node again. Fig.5.3 illustrates the third move of sink-node, it attempts to pull data from node 5 again. Since node 5 has already retrieved data from node 1 after sending its own data to sink-node in the first round, the childless node 1 is automatically disconnected from the routing tree and deleted from the child-list hold by its parent node 5. Upon getting data requirement message from sink node 0, node 5 will reply with the node-1's data on hold and subsequently require data from its second child node 19, on the other hand, when node 5 is engaging with node 0, node 11 is getting data from its child-node node 6 and waiting for the requirement from node 1 again. This systematic procedure continues until all data bulks are collected and the routing tree shrinks to zero.

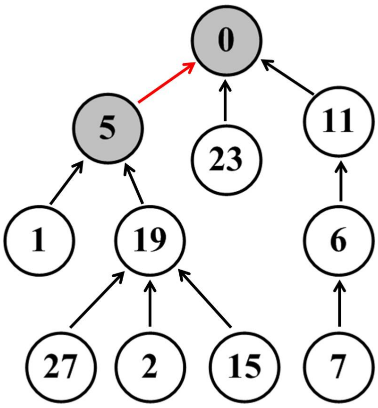

Figure 5.1: First step

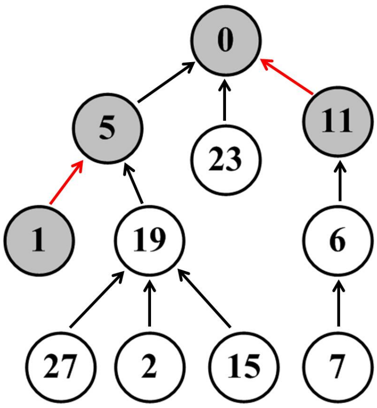

Figure 5.2: Second step

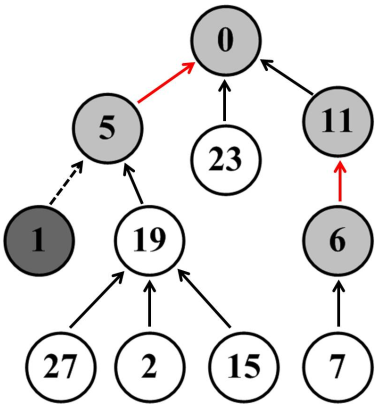

Figure 5.3: Third step

### 5.3.1 Theoretical formulation and proof of upmost efficiency

The data collection protocol described above has a theoretical formulation which can lead to a proof of its upmost efficiency. This subsection is dedicated to reveal the mechanism of the proposed data collection protocol. The formulation is based on the following important assumptions and definitions:

- The routing tree generated by the foregoing routing method is static and stable. No link change is allowed during the entire data collection process, and each operation of sensor nodes is successful as desired. This is an ideal assumption which can be hardly met in real applications, it is only imposed here for the theoretical formulation. For the practical implementation of this data collection protocol, these potential problems of instability will be included and considered in the next subsection.

- The time consumption of single-hop data transport is uniformly $t_{link}$ between any child-parent node pairs. Though this is strict assumption, it can be roughly satisfied given each node holds the same size of data and each link in the routing tree has reasonable link quality.

- The topology of any routing tree is expressed as $T = \{b_1, b_2, b_3, \ldots\}$ with $b_1 \geq b_2 \geq b_3 \geq \ldots \geq 0$ and $b_i$ being the indices of the sink-node branches(an index is defined as the number of remaining data bulks in a single routing tree branch of the sink-node). An operator *sort* is defined here to arrange a random array of non-negative numbers from the largest to smallest. Furthermore, a topology is equal to zero if and only if its first index is zero(which is to say all indices are zero following their descending order), and zero indices are omitted in a topology expression. Following this assumption, the initial topology in Fig.5.1 can be expressed as $T_0 = \{6, 3, 1\}$.

- A data collection cycle of the proposed data collection method is defined as two successive operations of the sink node, the first operation is pulling data from the currently selected branch node, while the second operation is either pulling from the next selected branch node or waiting (as explained earlier, pulling in case of having multiple active branches, waiting in case of having single active branch), since both pulling and waiting take $t_{link}$, a cycle period $t_{cycle}$ is thus equivalent to $2t_{link}$, and a cycle operator is defined as $P$ for convenience. Fig.5.1 and Fig.5.2 illustrate the first data collection cycle of this method. Since multiple active child-nodes are present for the sink-node, each operation of sink-node in this cycle is data pulling.

- A node function n(T) is defined to return the total number of remaining data bulks in a specific topology $T$, and a time function t(T) is defined to return the total time required for collecting all the remaining data bulks from $T$ using the proposed data collection protocol.

Under these assumptions, several conclusions about hop-by-hop data collection and the proposed collection protocol can be drawn and they are explained below.

First, the minimum time required for the sink node to collect all data bulks in a hop-by-hop manner from one routing tree branch with an index of $b$ is $(2b-1)t_{link}$, this is a trivial conclusion since the first layer node will deliver $b$ data bulks to sink node as well as pull $b-1$ data bulks from its own children, these operations are non-overlapping and each takes $t_{link}$ to finish. However, this conclusion leads to a lower bound of the total time required to collect all data bulks from a topology $T$ with a node number of $n(T) = N$:

$$t(T) \geq max(Nt_{link}, (2b_1 - 1)t_{link}) \tag{5.1}$$

Second, the cycle operator $P$, once applied on a non-zero sensor topology $T_i$, will results in a new topology $T_{i+1}$ depending on the second index of $T_i$:

$$PT_i\{b_1^i, b_2^i, b_3^i, \ldots\} = T_{i+1}\{b_1^{i+1}, b_2^{i+1}, b_3^{i+1}, \ldots\} = \begin{cases} sort\{b_1^i - 1, b_2^i - 1, b_3^i, \ldots\} & \text{if } b_2^i \geq 1 \\ sort\{b_1^i - 1, 0, 0, \ldots\} & \text{if } b_2^i = 0 \end{cases} \tag{5.2}$$

This conclusion follows directly from the foregoing assumption of the cycle operator $P$ and the knowledge of the largest tree branch selection mechanism of sink node. As an example, a comparison between Fig.5.1 and Fig.5.3 reveals the difference between $T_0$ and $T_1$, since data bulks from node 5 and node 11 have already been retrieved by node 1 during the first data collection cycle, the remaining data bulks on these branches thus decrease by one, and we have $T_1 = \{5, 2, 1\}$ as expected.

Third, the case of only one active branch exists for sink node, namely the case where $b_2 = 0$, is an undesirable routing topology for efficient data collection, as in such cases the sink node will be idle when its single child is pulling data from its own child-nodes, which results in extra time consumption and decrease the data collection efficiency. This is also seen from Eqn.(5.2), with $b_2^i = 0$, each cycle of data collection only reduce the total number of remaining data bulks by one, namely $n(T_{i+1}) = n(T_i) - 1$, while in comparison, when $b_2^i \geq 1$, we have $n(T_{i+1}) = n(T_i) - 2$ instead. Thus, the desired data collection protocol should be able to avoid or delay the formation of single branch during data collection process. It will be shown that the proposed data collection method achieves the upmost efficiency by following exactly this conclusion.

Fourth, the formation of single branch is unavoidable during the data collection process if and only if $b_1 > \sum_{i \neq 1}^{m} b_i$ with m being the total number of the initial sink node branches. This conclusion can be easily drawn from Eqn.(5.2), since under such a condition, with the continuous performance of cycle operator $P$, all the other indices will eventually become zero while leaving only the first index positive, indicating the formation of single branch. The topologies satisfying such a condition are classified into a topology subset defined as $\mathbf{T_S}$. Obviously, its complement subset includes all the topologies that satisfy $b_1 \leq \sum_{i\neq 1}^{m} b_i$ and is defined as $\mathbf{T_N}$. Namely,

$$b_1 > \sum_{i\neq 1}^{m} b_i \Leftrightarrow T \in \mathbf{T_S} \tag{5.3}$$

$$b_1 \leq \sum_{i\neq 1}^{m} b_i \Leftrightarrow T \in \mathbf{T_N} \tag{5.4}$$

A necessary condition of $T_i \in \mathbf{T_N}$ is $b_2^i \geq 1$, therefor, Eqn.(5.2) can be restated in the following form:

$$PT_i = T_{i+1} = \begin{cases} sort\{b_1^i - 1, b_2^i - 1, b_3^i, \ldots\} & \text{if } \mathrm{T}_i \in \mathbf{T_N} \text{ or } T_i \in \mathbf{T_S} \text{ with } \mathrm{b}_2^i \geq 1 \\ sort\{b_1^i - 1, 0, 0, \ldots\} & \text{if } \mathrm{T}_i \in \mathbf{T_S} \text{ with } \mathrm{b}_2^i = 0 \end{cases} \tag{5.5}$$

Understanding these conclusions, it is ready to show the mechanism of the proposed data collection protocol. The cycle operator $P$, has two desirable properties:

First, topology conservation, for any non-zero topology $T_i$, the following equation stands:

$$T_{i+1} = PT_i = \begin{cases} \in \mathbf{T_N} \text{ or } = \{1\} & \text{if } T_i \in \mathbf{T_N} \\ \in \mathbf{T_S} & \text{if } T_i \in \mathbf{T_S} \end{cases} \tag{5.6}$$

Second, steady shrinkage of the biggest branch, for any non-zero topology $T_i \in \mathbf{T_S}$, we have

$$b_1^{i+1} = b_1^i - 1 \tag{5.7}$$

The proof of these properties follow straightly from Eqn.(5.3), Eqn.(5.4) and Eqn.(5.5). These properties will be further used to prove that the proposed data collection method is always able to achieve the lower bound of total data collection time as defined in Eqn.(5.1).

Assuming an initial topology $T_0 \in \mathbf{T_N}$ with $n(T_0) = N$ and the proposed data collection protocol being employed to collect data. Following Eqn.(5.5) and Eqn.(5.6), it can be inferred that $T_{N/2-1} = \{1, 1\}$ for an even $N$ as well as $T_{(N-1)/2} = \{1\}$ for an odd $N$ under the successive application of cycle operator $P$. Since each cycle consumes $t_{link}$, in the first case, we have

$$t(T_0) = (\frac{N}{2} - 1)t_{cycle} + t(\{1, 1\}) = \frac{N}{2}t_{cycle} = Nt_{link}$$

while for the second case,

$$t(T_0) = \frac{N-1}{2}t_{cycle} + t(\{1\}) = (N-1)t_{link} + t_{link} = Nt_{link}$$

Therefore, without distinguishing $N$, it always stands that

$$t(T_0) = Nt_{link} \tag{5.8}$$

for any $T_0 \in \mathbf{T_N}$ with $n(T_0) = N$.

Similarly, for an initial topology $T_0 \in \mathbf{T_S}$ with $n(T_0) = N$, it is easily predicted that $b_2^{\sum_{i\neq 1}^m b_i^0} = 0$ after applying the $P$ operator $\sum_{i\neq 1}^m b_i^0$ times successively on $T_0$. Therefore, single branch for sink-node will be initially formed when $T_{\sum_{i\neq 1}^m b_i^0} = \{b_1^0 - \sum_{i\neq 1}^m b_i^0\}$. After the formation of single branch, the second equation of Eqn.(5.5) will be evoked, one cycle of the proposed data collection protocol will and only will decrease the total number of uncollected data bulks by one following the steady shrinkage of the biggest branch property of $P$. With such a procedure, we can derive an explicit expression of $t(T_0)$ for any $T_0 \in \mathbf{T_S}$ with $n(T_0) = N$,

$$t(T_0) = \sum_{i\neq 1}^{m} b_i^0 t_{cycle} + (2(b_1^0 - \sum_{i\neq 1}^{m} b_i^0) - 1)t_{link} = (2b_1^0 - 1)t_{link} \tag{5.9}$$

Combining Eqn.(5.8) and Eqn.(5.9), an expression of the total data collection time for any sensor topology $T_0$ using the proposed data collection protocol can be eventually formulated as:

$$t(T_0) = \begin{cases} Nt_{link} & \text{if } T_0 \in \mathbf{T_N} \\ (2b_1^0 - 1)t_{link} & \text{if } T_0 \in \mathbf{T_S} \end{cases} \tag{5.10}$$

A comparison with Eqn.(5.1) reveals that the proposed data collection protocol is always able to achieve the minimum data collection time independent of the initial sensor topology.

### 5.3.2 Practical Implementation and Failure Compatibility

Though the proposed data collection protocol is extremely efficient theoretically, practical implementation requires some compromise of efficiency for stability. For example, as described in the last subsection, the upmost efficiency of the proposed data collection protocol is predicated on a static routing tree, the success of every single operation as well as the uniform $t_{link}$ of single-hop data transport. Though the foregoing routing protocol provides a robust function to generate such high-quality bidirectional static links, these conditions are still difficult to meet in real applications. The existence of unexpected problems can seriously jeopardize the stability of the desired application, moreover, we might risk losing all child-node data from an intermediate parent-node if this parent-node fails communication due to the unchangeable topology links. Therefore, failure compatibility including a certain topology update mechanism is a critical feature to be incorporated in the program design of the proposed data collection protocol. During program development, various failure modes of single-hop data transport have been observed, but basically, they can be classified into three categories: flash memory failure of child node, data transmission timeout and no communication response from child-node. The first failure mode is usually attributed to a failure in sensing period when sensor node attempts to store data into flash memory, when it happens, a sharp decrease of $t_{link}$ is expected since the failed child will no longer send data back to its parent but rather send a flash-fail message notifying its parent the failed status of itself, and the packet size of this message is much smaller than the real data size. The second failure mode are commonly observed when the communication environment is lossy, single-hop data transport consumes much more time and becomes unpredictably long, a timeout event is usually triggered to end the single-hop data transport and return failure status to the parent-node. The third failure mode can be either due to node power issue or delay of radio channel switch, in this case, child-node will miss the data requirement message from the parent-node and thus the parent-node will not be able to successfully retrieve data from its child-node as demanded by the proposed data collection protocol. All these failure modes needs consideration for the program stability.

In the developed program, several additional features are implemented along with the core algorithm of the proposed data collection protocol. These features provide critical enhancement that makes the implementation of the proposed method effectively failure-tolerant.

The first feature aims at solving the possible radio channel switch delay by using a cycle number attached in each data requirement message from parent-node to child-node, this cycle number notifies the child-node the approximate period it will be scanned for data by the parent-node again. This period is conservatively evaluated from branch numbers on all the upper layers. With this cycle number, a child-node can perform multiple data retrieving trials from its own child-nodes if allowed, and always turn its radio channel back in time so as not to miss the data requirement message from its parent-node.

The second feature is generally for every possible failure modes. After data collection process starts, each child-possessing node in the network keeps a failed-node-list of all its child/grand-child nodes. When any communication failure happens between a parent-child node pair, the parent-node will add the failed child-node into its failed-node-list, and this list will be passed to its own parent-node in the next data retrieving cycle. Upon receiving the failed-child-list from child-node, a parent-node will incorporate the received list with its own to keep failure information updated. A node is taken out of the failed-child-list of its higher layer parent/grand-parent node if its data is retrieved in subsequent cycles and arrives at this higher layer node. Furthermore, a link between a failed child-node and its parent-node is severed if the communication of this link fails three times consecutively. Enhanced with this feature, the developed program is able to properly handle and control communication failure in the entire network as well as to guarantees the systematic convergence of the proposed algorithm is not hindered by any possible communication failures. However, an inevitable side-effect from this feature entails the inclusion of third feature described below.

The last feature is included to provide the program an ability to locally adjust topology links. For convergence of the proposed data collection protocol, the second feature assures that links that fail three times consecutively is automatically cut by the parent-node, this causes a risk of losing all child-node data from an intermediate node if this node is cut by its own parent-node due to their failed communication trials. To circumvent this risk, a specific local topology update mechanism is designed in keeping with the proposed data collection algorithm. The local link adjustment mechanism is proposed for a grand-child-node with a failed intermediate parent-node as the original path to its grand-parent-node. When the grand-parent-node cannot successfully communicate with the intermediate parent-node three times consecutively, it deems the parent-node as inactive, cuts the link from the parent-node, and also attempts to seek new intermediate nodes for the grand-child-node in order to prevent data loss from the entire branch. In this case, the grand-parent-node will broadcast HELP messages upon cutting the failed link from parent-node, the HELP messages will travel to the grand-child-node through other intermediate nodes if they exist, the grand-child-node will pick the source of the HELP message with the highest RSSI value and the same grand-parent-node as a new path to its original grand-parent-node. Since the grand-child-node is still routed to its original grand-parent-node after the routes adjustment process, the index of each routing tree branch kept at the upper-most sink-node will not be invalidated by this local topology update, and thus the proposed data collection algorithm is still effective and efficient. This process can be well implemented if there are multiple available intermediate nodes with a link to the same grand-parent-node. However, such backup parent-nodes may not always exist in real wireless monitoring systems for civil infrastructures where the topology of sensor nodes are typically linear. Under such a condition, the grand-child-node will not distinguish the HELP messages from upper layers and only select the message with the strongest signal strength.

The detailed program design of the proposed data collection protocol are shown in Fig.5.4 and Fig.5.5.

### 5.3.3 Application examples

The proposed data collection protocol has been implemented on Imote2 smart sensor platform and a series of experiments have been conducted to evaluate its data collection efficiency. Examples presented in this section will show its practical applicability as well as its upmost data collection efficiency. The experiments were conducted in the laboratory environment by turning down the radio power of each sensor nodes, thus a multi-hop network can be easily created in a relatively small space. Sensor positions were changed after each experiment to create a new topology. Different failure modes were simply simulated by randomly taking out several

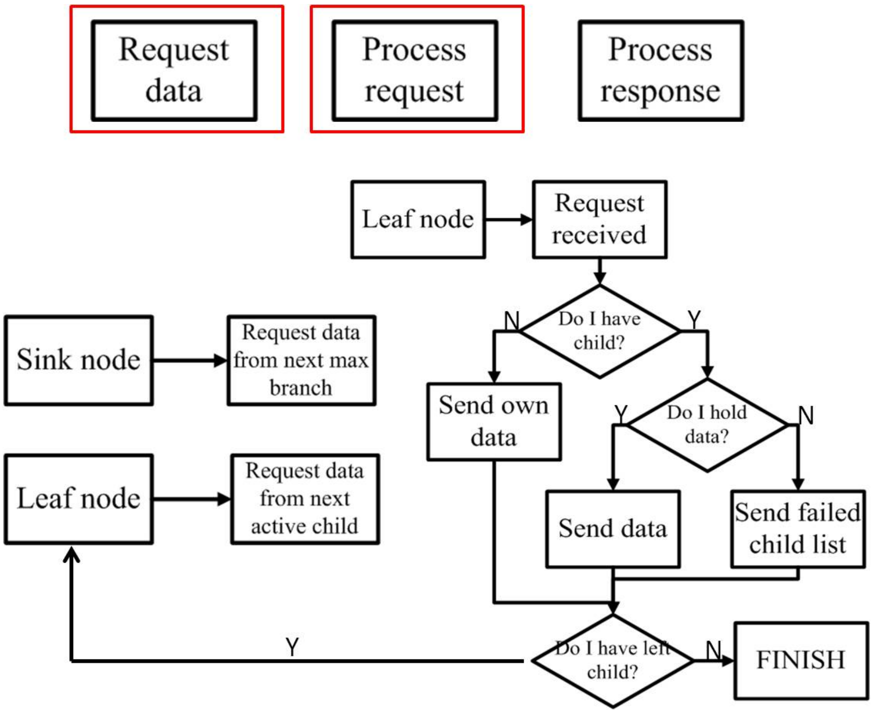

Figure 5.4: Multi-hop data collection program design Part 1

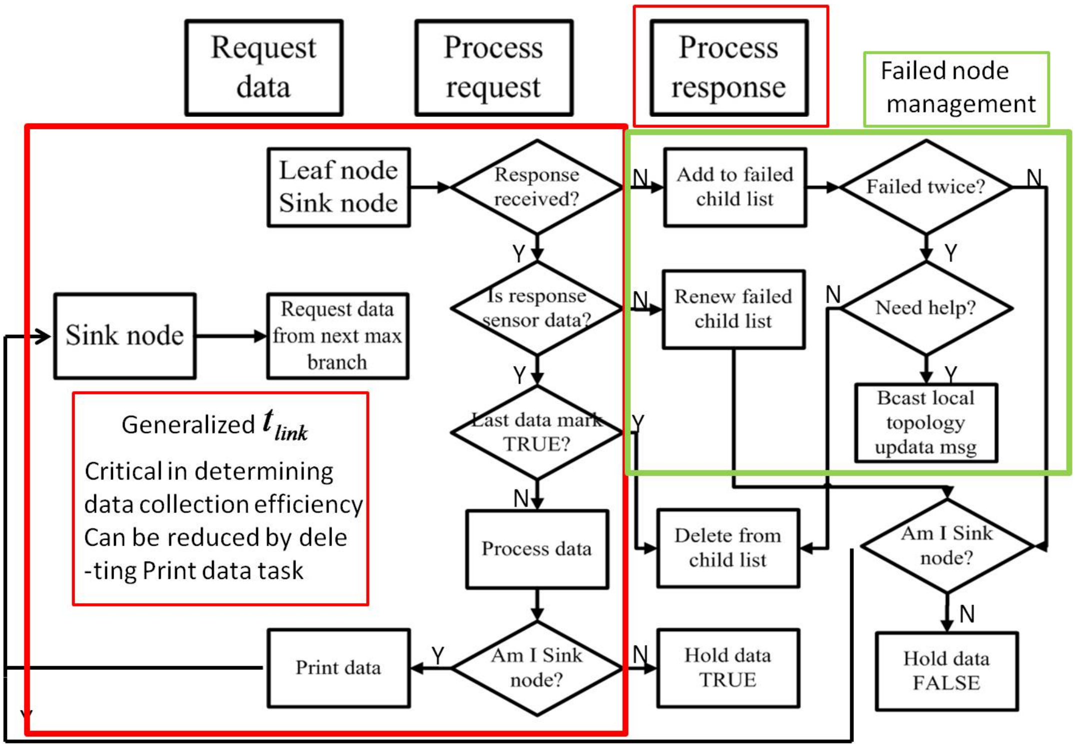

Figure 5.5: Multi-hop data collection program design Part 2

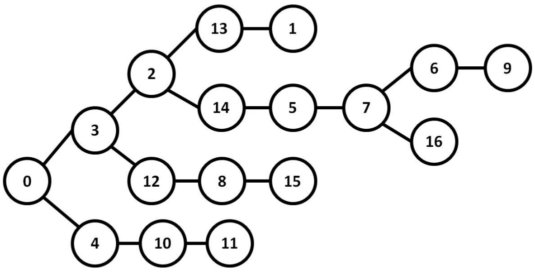

Figure 5.6: Topology 1: $T_0 = \{13, 3\} \in \mathbf{T_S}$

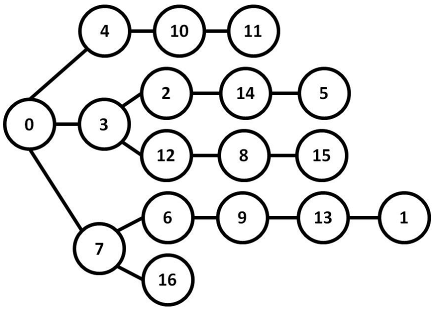

Figure 5.7: Topology 2: $T_0 = \{7, 6, 3\} \in \mathbf{T_N}$

sensor nodes after the routing tree has already been generated. In total 16 sensor nodes were used in the experiment and each sensor node has 192kB data stored on the flash memory. The time consumption of single-hop data transport $t_{link}$ is measured and averaged from multiple pre-tests. A value of 18 seconds is finalized as the most reasonable approximate of $t_{link}$. The sensor topologies are shown in Fig.5.6 to Fig.5.9.

For the experiments of data collection with failed nodes, topology 1 and topology

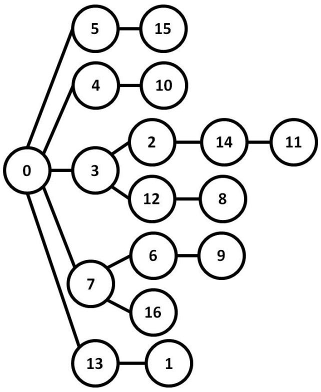

Figure 5.8: Topology 3: $T_0 = \{6, 4, 2, 2, 2\} \in \mathbf{T_N}$

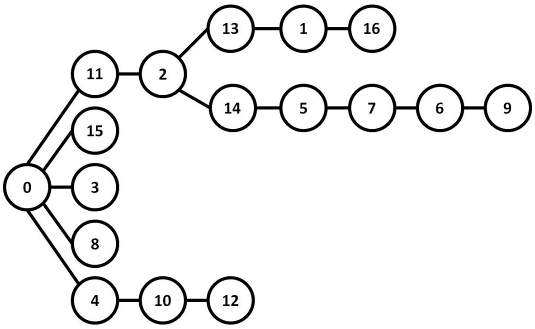

Figure 5.9: Topology 4: $T_0 = \{10, 3, 1, 1, 1\} \in \mathbf{T_S}$

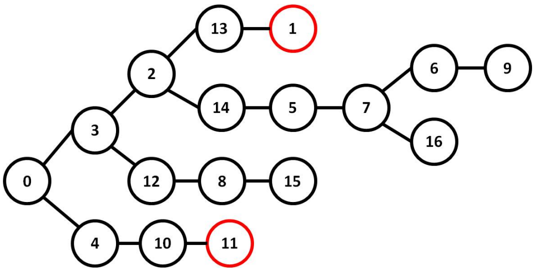

Figure 5.10: Topology 1 with 2 failed nodes

3 were employed, two different nodes were taken out from the topologies respectively. As shown in Fig.5.10 and Fig.5.11. Since node 7 taken from the topology 3 has child-nodes, the local topology update mechanism was triggered during the data collection process, and its child-nodes 6 and 16 re-linked to two other intermediate nodes and renewed their paths to the sink-node 0. The renewed topology is shown in Fig.5.12.

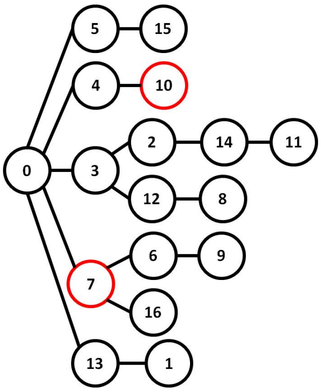

Figure 5.11: Topology 3 with 2 failed nodes

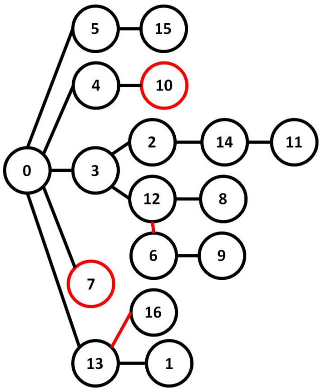

Figure 5.12: Topology 3 with updated routes

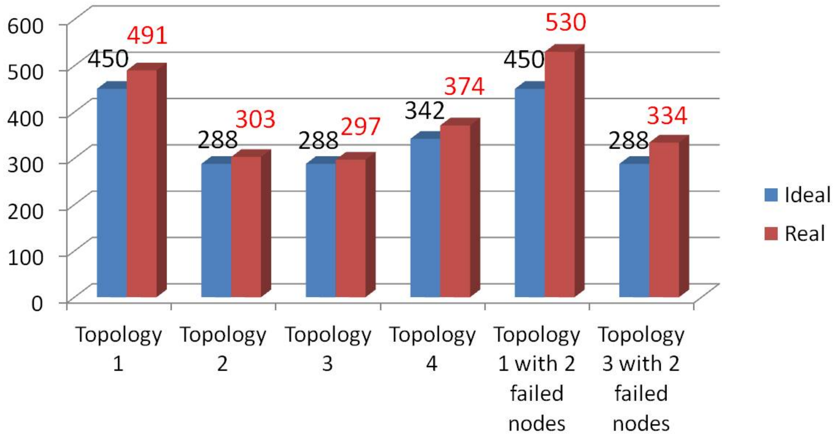

Figure 5.13: Results of multi-hop data collection experiments

The theoretical minimum time consumption using $t_{link} = 18s$ and the real time consumption for each topology are shown in Fig.5.13. As demonstrated by the experiments, the proposed data collection method is very efficient independent of network topology, it has an almost perfect data throughput when no communication failure happens and still a quite high throughput when a small number of nodes failed due to different reasons.

## 5.4 Conclusion

In this chapter, an efficient multi-hop service for the developed dynamic event monitoring system including flooding command dissemination, multi-hop routing and multi-hop data collection is developed and presented in details. The proposed multi-hop data collection protocol is proved to be able to achieve the maximum efficiency allowed by a hop-by-hop data transport scheme. Moreover, it is enhanced with several additional features for possible communication failure treatment. The developed programs were implemented and evaluated, it is shown that the developed protocol is not only able to achieve high data collection efficiency but also is robust against failure nodes.

# Chapter 6

# Experimental Applications

In this chapter, two full scale application examples are given to further show the applicability and evaluate the performance of the developed system. The first example is done on Hongo Campus of University of Tokyo with an aim to evaluate the multi-hop communication service developed in Chapter 5, while the second experiment is conducted on Rainbow Bridge to evaluate the system performance on real full scale civil infrastructures.

## 6.1 On campus test

Before the rainbow bridge measurement described in the next section, a series of on campus tests were conducted on Hongo Campus of University of Tokyo from July 14th to 16th, 2012. The purpose of these tests is to validate the program applicability and evaluate the multi-hop communication service on full scale implementations. Fifteen sensor nodes were employed in the experiment and put along the alley between Engineering Building NO.1 and the central library of Hongo Campus. A typical sensor layout is shown in Fig.6.1. The sensors and antennas are shown in Fig.6.2 and Fig.6.3 respectively.

During the two days tests, data communication problems were observed when

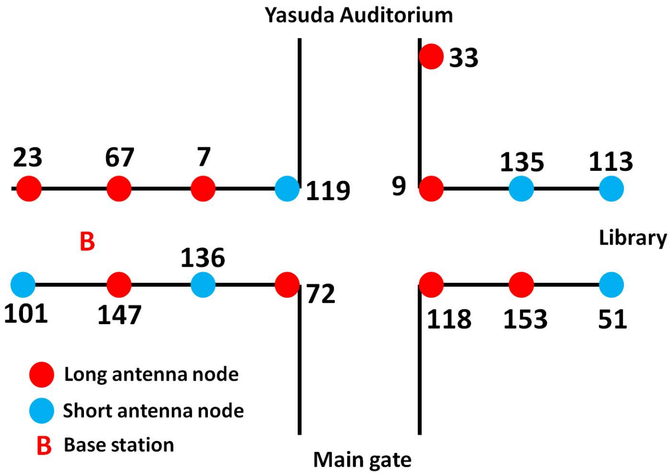

Figure 6.1: On campus test: sensor layout

Figure 6.2: On campus test: sensors

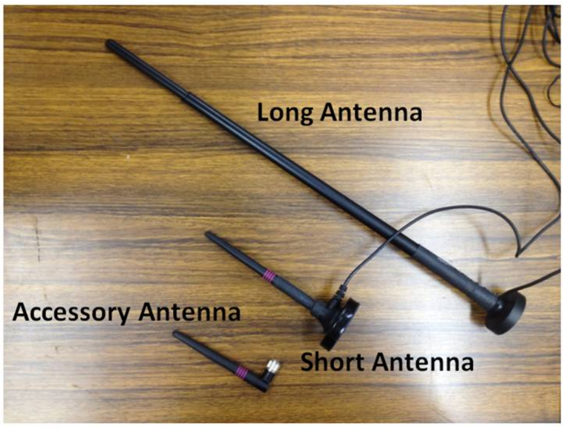

Figure 6.3: On campus test: antenna

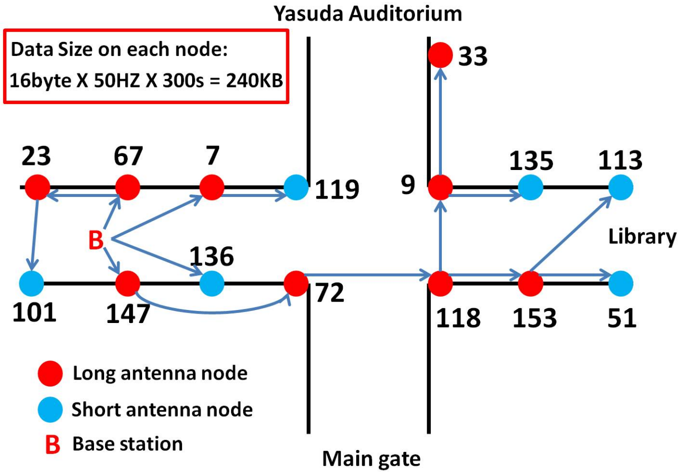

Figure 6.4: On campus test: generated routes

the sensors are separated over 40 meters and the node links become very lossy. This problem and the potential reasons will be further discussed in the conclusion part of this chapter. Fig.6.4 shows one successful example of the multi-hop communication program. Each sensor node has 240kB data on hold. The routes generated by the multi-hop routing method are shown in blue. Following the rules of the Chapter 5, the topology of this case can be expressed as $T_0 = \{9, 3, 2, 1\}$, and obviously, $T_0 \in \mathbf{T_S}$. Assuming a 10kB/s single-hop data throughput(which is reasonable from previous researches), we have $t_{link} = 24s$, and thus the ideal data collection time from the entire network is estimated to be $(2 \times 9 - 1)t_{link} = 408s$. The comparison between the actual data collection time and the ideal time consumption is given in Fig.6.5. The over 70 seconds difference is mainly due to the fixed waiting time after the formation of single-branch.

In summary, the two-days tests not only revealed the data communication problems when sensor links become lossy but also demonstrated the applicability of the developed system for full scale implementations. As pre-tests of the rainbow bridge measurement, it prepared us for any possible results we might encounter during the real measurement.

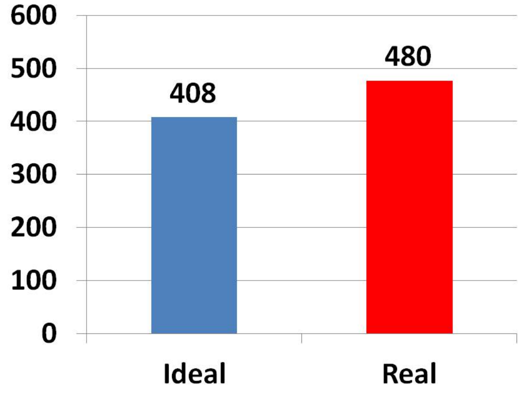

Figure 6.5: On campus test: result

## 6.2 Rainbow Bridge Measurement

A full scale application was conducted on Rainbow Bridge on July 17th, 2012. The main target of this measurement is to evaluate the system performance under harsh communication environment of real civil infrastructures. In total 43 sensors nodes were instrumented in the measurement, and their locations on the bridge are given in Fig.6.6. The main span of Rainbow Bridge has a length of 570 meters, and its side spans both have length of 114 meters, and towers have height of over 70 meters from the girder. Basically, all spans and towers were covered in the measurement. Similar to the highway bridge measurement described in Chapter 3, the system is controlled and triggered by manually generating large vibrations to the head-nodes because no specific dynamic event during the measurement period could cause an exceptionally large response of the bridge.

At last, 24 nodes among the 43 installed have successfully recorded vibration data, and the successful nodes are shown in Fig.6.7 in red numbers. The other node failures were mostly due to battery issues, communication failures and hardware instabilities. Data examples from 4 sensor nodes are given in Fig.6.9 and Fig.6.10. Due to some unidentified reasons, lower modes of the bridge were not successfully captured by the monitoring system and the data records were not able to produce a reasonable modal analysis result.

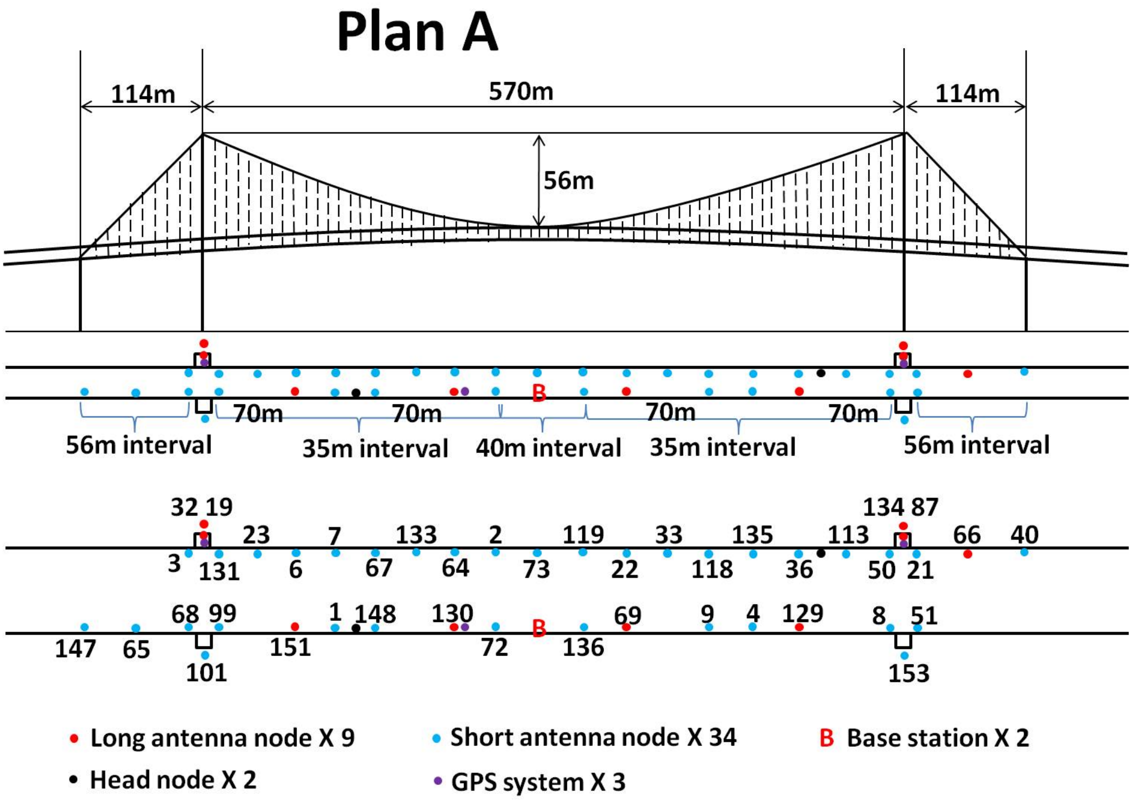

Figure 6.6: Rainbow Bridge Measurement: plan

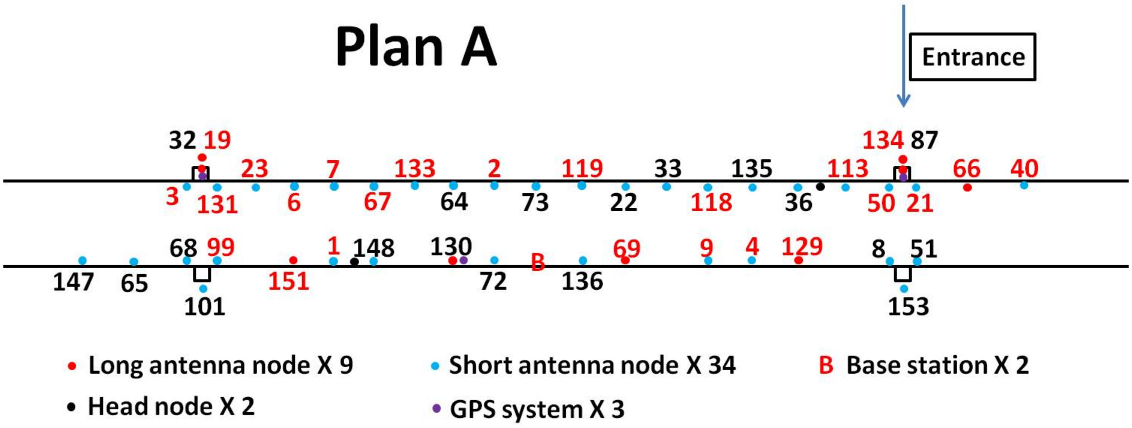

Figure 6.7: Rainbow Bridge Measurement: successful nodes

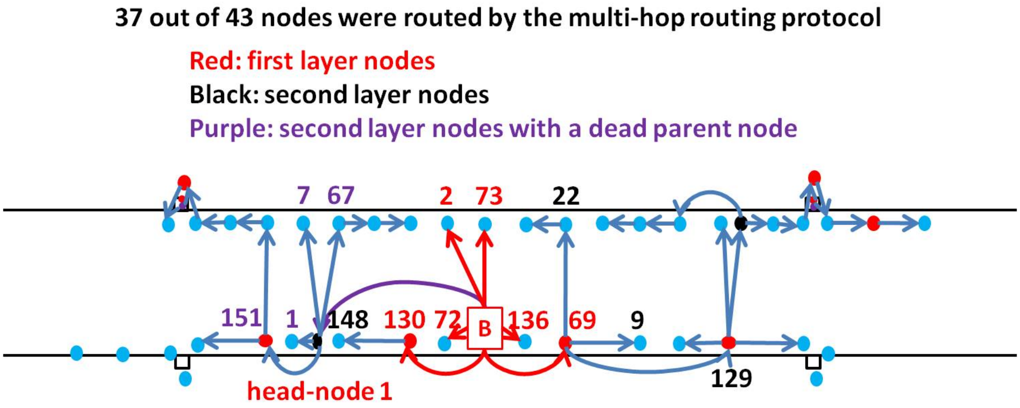

Figure 6.8: Rainbow Bridge Measurement: multi-hop routes

The multi-hop data collection was not so successful either. At best 37 nodes out of 43 were routed after sensing stops. The established routes were shown in Fig.6.8. The topology can be expressed as $T_0 = \{18, 13, 2, 1, 1, 1, 1\}$. The first layer nodes are shown in red numbers while the second layer nodes are shown in black and purple. The data collection process only returned six sets of data from head-node 1, 151, 1, 67, 69 and 2 respectively. Then the links between base-station and head-node 1, base-station and 69 were cut due to multiple failed communication trials(these are very low-quality and lossy link with an RSSI value of -90). HELP message were broadcasted by base-station but the child-nodes of head-node 1 and 69 were not able to renew their routes back to the base-station. Data bulks from these entire branches were lost. The reason is thought to be lack of redundant routes. For example, when head-node 1 is cut by the base station, all its layer 2 child-nodes(in purple) are in need of a new parent-node to base-station, but since only the first layer nodes and second layer nodes were qualified to participate in the link adjustment process, and none of them(in red and black numbers) can directly communicate with the nodes needing help, this undesirable condition resulted in losing data from the entire branch of head-node 1. Similar case happened for node 69. Therefore, the data collection efficiency were not properly evaluated for this measurement.

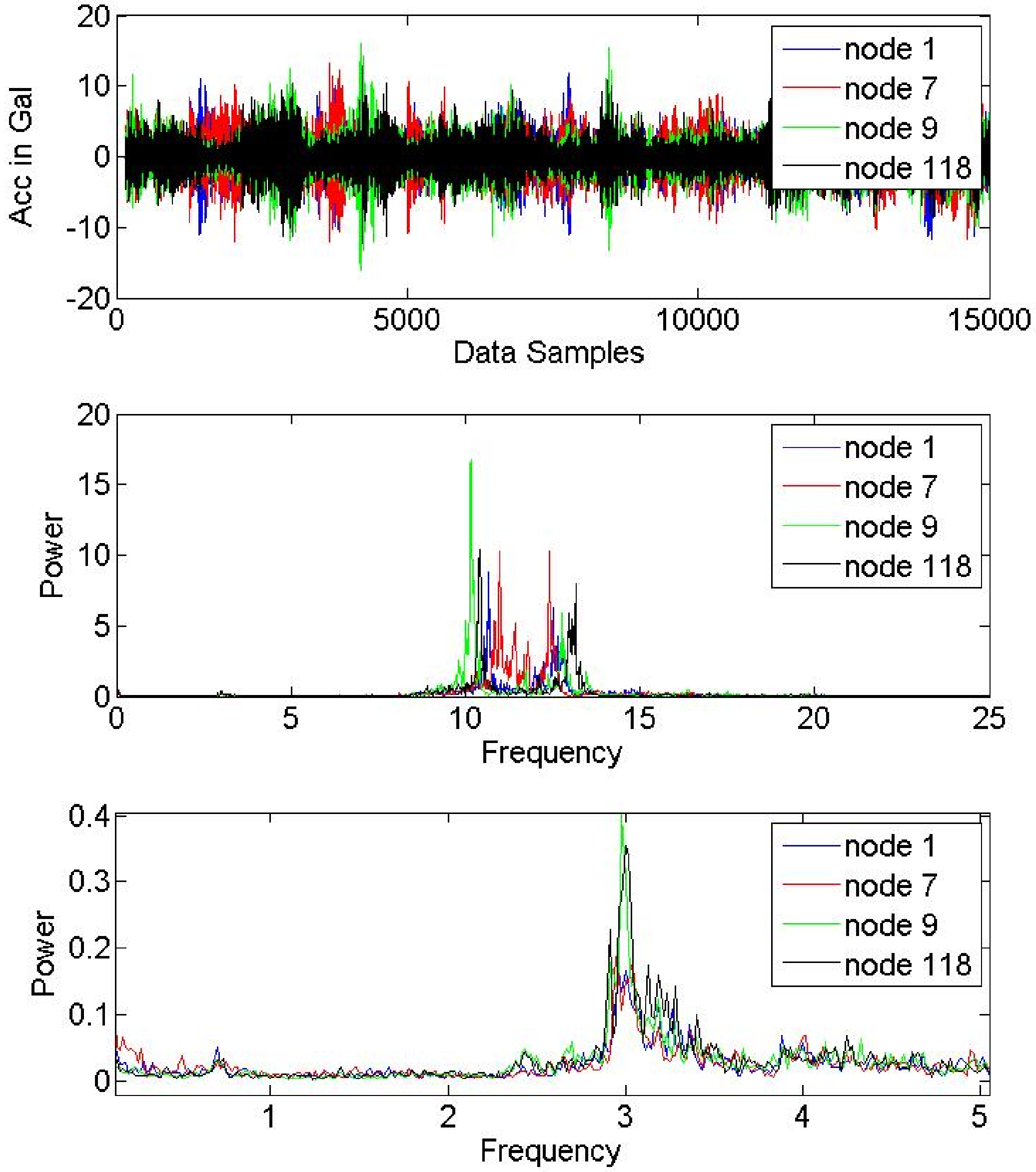

Figure 6.9: Rainbow Bridge Measurement: vertical response

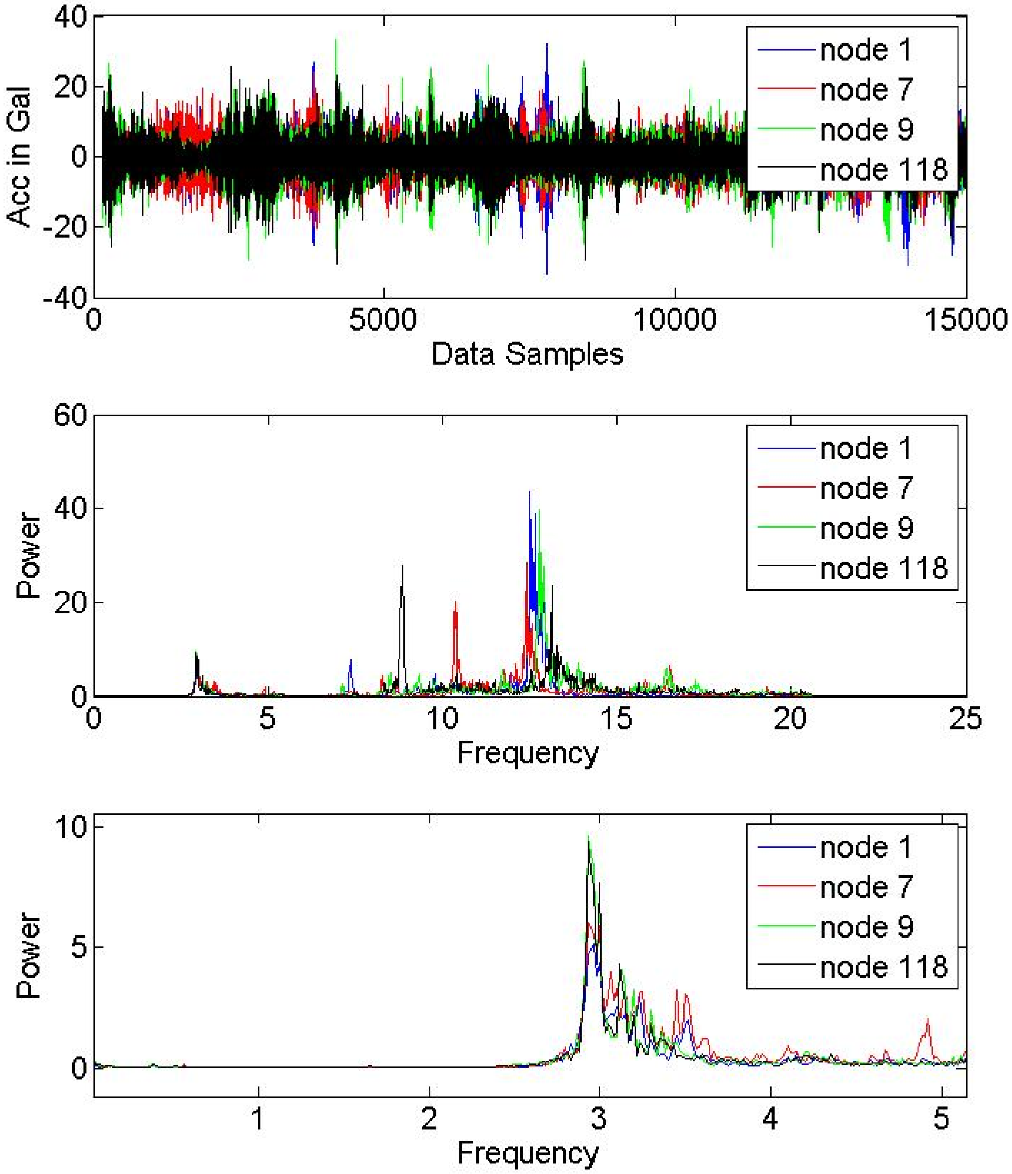

Figure 6.10: Rainbow Bridge Measurement: lateral response

In conclusion, the Rainbow Bridge Measurement revealed the potential problems of the developed system under the harsh communication environment of real civil infrastructures. The problems and possible solutions will be detailed in the next section.

## 6.3 Conclusion

In this chapter, two full scale application examples of the developed system are presented. Through these two experiments, potential problems of the systems can be identified. These problems and possible solutions are explained below:

- Low link-quality single-hop data communication is unstable and unreliable under very lossy conditions, it should be avoided for data transport in multi-hop data collection process. For example, when the sensors are separated almost at the distance of communication limit, the successful packet rate of single-hop communication becomes so low that the corresponding data transport usually fails and ends by time-out, resulting in communication failures in the multi-hop data collection protocol. If all of the sensors are separated at such distances, the multi-hop data collection usually terminates at a very early stage. The solution to this problem is to place the sensors at distance that single-hop communication can have a reasonable performance or with a bilateral link quality of at least -85.

- The proposed local link adjustment procedure, in order to assure loop-freedom and shortest-path-to-sink, only involves two adjacent layers of sensor nodes, when these nodes are separated by distance, usually no redundant routes are available for link adjustment. This is the common condition when the physical sensor topology becomes linear or sensor nodes are widely separated. One possible solution is to involve more nodes in the link adjustment procedure, however, in this case, loop-freedom should be carefully handled.

- The developed system, especially multi-hop data collection protocol, has low performance under very lossy conditions. Because under such conditions, frequent failure of single-hop data communication triggers frequent local topology update which can be hardly all accommodated by this data collection protocol specifically designed for static sensor networks. Also, under such lossy environment, redundant links with reasonable quality are usually not available, causing massive data loss from failed branch nodes. The solution again would be placing the sensors at distance that single-hop data communication can have a reasonable performance, this can assure that the multi-hop data collection protocol mainly resorts to a static network with infrequent link changes.

# Chapter 7

# Conclusions and future work

## 7.1 Conclusion

This research has developed a complete framework of a wireless smart sensor network based seismic response monitoring system, which can also be readily used for general dynamic event monitoring, for civil infrastructures. The developed framework contains three distinctive modules solving different challenges. With suitable hardware platforms, the developed framework can result in a long-termly stable wireless seismic response monitoring system with easy deployment and efficient multi-hop communication, it also has a potential to provide a simple and low-cost alternative to the current monitoring systems.

The data acquisition module for general dynamic events monitoring described in chapter 3 is built on a quick and stable event detection method. This method includes different mechanisms developed to overcome the potential instabilities of the wireless sensor board as well as outside interference, with minor adjustment of parameters, it can quickly and stably detect the transient events of interest by checking the abnormal vibration records. Examples are also provided to show its applicability for various monitoring purposes.

The designed sensor box integrates AC power cable with rechargeable batteries, it can provide a long-termly stable power source for individual wireless sensor nodes. This is an essential factor for the realization of seismic response monitoring which requires sensors continuously running for a long-term.

The customized long-term time synchronization protocol is another enabling component for long-term seismic response monitoring, it can provide a network-wide accurate time synchronization through a long sensing period. This is very important for each sensor node in the monitoring system to provide consistent time records of their stored seismic response. Example has shown long-term accurate time synchronization can be achieved by the developed program.

The efficient multi-hop communication service developed in chapter 5 provides a flooding-based command dissemination, an improved multi-hop routing protocol and a theoretically most efficient data collection protocol. Their process are explained in details and the possible problems in program implementation are addressed by incorporating several additional features. The efficiency and failure-robustness of the proposed data collection protocol are demonstrated by several examples.

The developed system were finally applied to two full-scale experiments. The results demonstrated its applicability while also revealed the potential problems. The problems were specifically identified and possible solutions were also discussed.

In conclusion, this research presented a novel development of a stable long-term autonomous dynamic event monitoring system using wireless smart sensor network. Different components of the system were presented in depth and validated by examples. The next section will describe the possible future works that should be done before the developed system can really be implemented for general civil infrastructures.

## 7.2 Future work

Due to the limitations of this research. Future works are suggested before the actual long-term implementation of the developed system for the purpose of seismic response monitoring. These future works are summarized here for reference.

First, hardware instabilities have been observed by the author during program development. Some of these problems were solved in the program development, for example, the sensor data spikes. Some are still left, for example, high sampling frequency(more than 100HZ) will result in the decreased system life. These instabilities should be addressed by improving the hardware design or other compensation methods. Future work is suggested to locate the reasons of instability and eliminate them for a more stable monitoring system.

Second, more full-scale infrastructure test of the system. Though this research has included many laboratory experiments and several full-scale tests of the developed system, more full-scale structure tests are still advised to further debug the developed programs. Also, full-scale structure tests are suggested for long-term(more than one month) implementation of the system, long-term multi-hop synchronization tests and large-network large-data-size multi-hop data collection test.

Third, power harvesting. Though the developed system uses external power source to support the long-term running of the system. These power source may not always be available. A promising and better choice would be using node-level power harvesting systems. Integration of these systems can further widen the application areas of the developed system.

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