Development of a Low-cost Wireless Sensor Network for Monitoring of Earthquakes in Developing Countries

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SUMMARY:
National governments in developing countries heavily invest in infrastructures in cities and economic zones that cradle economic growth and development in particular regions of the country. Countries located in the earth's ring of fire have the added challenge of maintaining these capital-intensive infrastructures in order not to stall economic growth after an earthquake. However, cities and economic zones in developing countries lack the monitoring system that is needed for earthquake warning, post-disaster applications and developmental research. This paper presents the development of a Wireless Sensor Network (WSN) for earthquake monitoring. Its low cost makes it suitable for implementation in cities and economic zones in developing countries. The use of MEMS accelerometers greatly reduces the cost compared to other systems already in the market. The pilot system is composed of six slave nodes and a base station node. The slave nodes are mote platforms equipped with a tri-axial accelerometer and a radio chip for wireless data transmission. Vibrations measured by the slave nodes are transmitted wirelessly until it reaches the base station node, which acts as the data sink, and is responsible for the serial interface of the (base station) PC to the sensor network. The base station node is also responsible for time synchronization of the system. Routing protocols, such as the multi-hop protocol, extend the wireless communication range of a node for wider coverage of large-scale deployments. Other protocols update the system model of the network for better reliability in case of failure of a single node. Lastly, the base station (PC) handles the logging and the storage of the data for future processing and analysis.

Keywords: Wireless Sensor Network (WSN), MEMS accelerometers, earthquake monitoring

1. INTRODUCTION

Past civilizations flourished as people congregated, organized themselves and built cities that became centers of commerce, education and government. This is still true today. Cities continue to attract people because of opportunities for growth that can only be found in organized communities led by a central government. Aside from cities, national governments in many developing countries set-up special economic zones as part of their development plan. These areas, initially undeveloped or may have a different use, become centers of economic growth as local and international investors are given incentives to establish their businesses in these special zones, providing employment opportunities for the people. Thus, national and local governments invest heavily on infrastructures in these areas because they cradle economic growth and development in different regions of a developing country.

The Philippines began implementing the Philippine Special Economic Zones Act in 1995 [Republic Act No. 7916, 1995]. This law identifies Special Economic Zones, or Ecozones, to include (1) Industrial Estates, (2) Export Processing Zones, (3) Free Trade Zones, and (4) Tourist and Recreational Centers. These economic zones are dispersed throughout the country in order to provide the economic stimuli needed for growth and development. For this to happen, the national and local governments inject a lot of capital and investment in the infrastructure development of an economic zone. As of December 2011, there are 352 economic zones dispersed in different regions of the country. These economic zones are contributing much to a sustained economic growth and it would stall the development of the country should these zones stop due to failure of existing infrastructures in the event of a destructive earthquake.

Current researches in developed countries have been pushing for the advancement of systems that monitor the structure (structural health monitoring or SHM) and/or the earthquake hazard. Farrar et al. 2007, said that this is because many infrastructures are close to reaching their peak life expectancy. All around the world, natural disasters have been occurring much for the past few years and have put forth a challenge to the engineers in coming up with a way to monitor the stability/fragility of a structure. Moreover, they believed that knowing if a structure has received significant damage through the years, the people will know if reoccupation within the range of the structure is safe. Not only that, an early warning can be done to local residents where a severely damaged structure is located.

Vibration-based monitoring is chosen as a means of measuring structural health because, not only are earthquake vibrations recorded and observed but, results from experiments of many researchers show that the frequency of vibration of a structure decreases as damage on the structure increases. Researchers around the world agree that a decrease in the frequency of vibration indicates an increase in induced damage to the structure in question. These have also been shown to be consistent with theoretical computations on dynamics of structures. Recently, vibration monitoring using wireless sensors is gaining a lot of attention because of its obvious advantages over that of traditional cable-connected sensors. Table 1.1 enumerates the advantages and disadvantages of wireless sensor networks (WSN) over wired systems.

Table 1.1 Comparisons between Wired and Wireless Networks.

Wired Sensor Network	Wireless Sensor Network
Reliable transmission	Packet losses
Long operating life	Limited operating life
Cannot handle node failures	Flexible with node failures
Small scale deployment	Large scale deployment
Fixed network hierarchy	Scalability of node capacity
Expensive wiring costs	Low maintenance and deployment costs

Some advantages of implementing wireless sensor networks are the elimination of costly site installations, the reduction of site visits, the easiness of monitoring several locations at a certain base station, the reduction of maintenance and inspection costs, the elimination of the unreliable monitoring caused by human errors, and many others.

One example of a wireless sensor network, conducted by Paek et al. 2005, is the WISDEN which implements a multi-hopping protocol wherein wireless sensor nodes are strategically placed at different locations and collected data are transmitted from a source node onto the base station through the help of the intermediate nodes by forwarding the message from the source node to the destination node. This system can transmit and receive time-synchronized tri-axial vibration data reliably at a sampling rate of 200Hz. The system focuses on three major criteria, and these are reliable transmission, time-synchronization, and data compression.

WSN is one growing trend in the engineering research community where engineers and peer researchers have been developing numerous implementations of wireless sensor networks that consist of a large density of sensor nodes deployed on a civil structure. Because of these efforts, authorities from different parts of the globe can now implement the technology in providing safety. Safety may be in the context of an early warning system, or an accurate damage assessment of a frequently inhabited structure, or simply the performance assessment of an industrial machinery and equipment.

2. ECONOMIC ZONES IN THE PHILIPPINES

The website of the Philippine Economic Zones Authority shows that Special economic zones are divided into the following types: (1) Industrial Estates (IEs) are tracts of land developed for the use of industries. (2) Export Processing Zones (EPZs) are special IEs whose locator companies are mainly export-oriented. (3) Free Trade Zones are areas nearby ports of entry, such as seaports and airports. Imported goods may be unloaded, repacked, sorted and manipulated without being subjected to import duties. (4) Tourist and Recreational Centers contain establishments that cater to both local and foreign visitors to the ecozones. Such businesses include hotels, apartments and sports facilities. As of December 2011, the Philippines has 159 Information Technology (IT) zones, 64 Manufacturing zones, 12 Tourism zones, 1 Medical Tourism Park, 1 Medical Tourism Center, and 15 Agro-industrial Ecozones; a total of 252 operating economic zones. Figure 1 shows the location of the 252 operating economic zones on the Philippine map. Moreover, there are 62 IT zones, 26 Manufacturing zones, 8 Tourism zones, and 4 agro-industrial ecozones; a total of 100 proclaimed economic zones. Another map shows the location of the 100 proclaimed economic zones on the Philippine map. The two maps clearly show the dispersion of the different ecozones throughout the country in order to stimulate economic growth in different regions of the country.

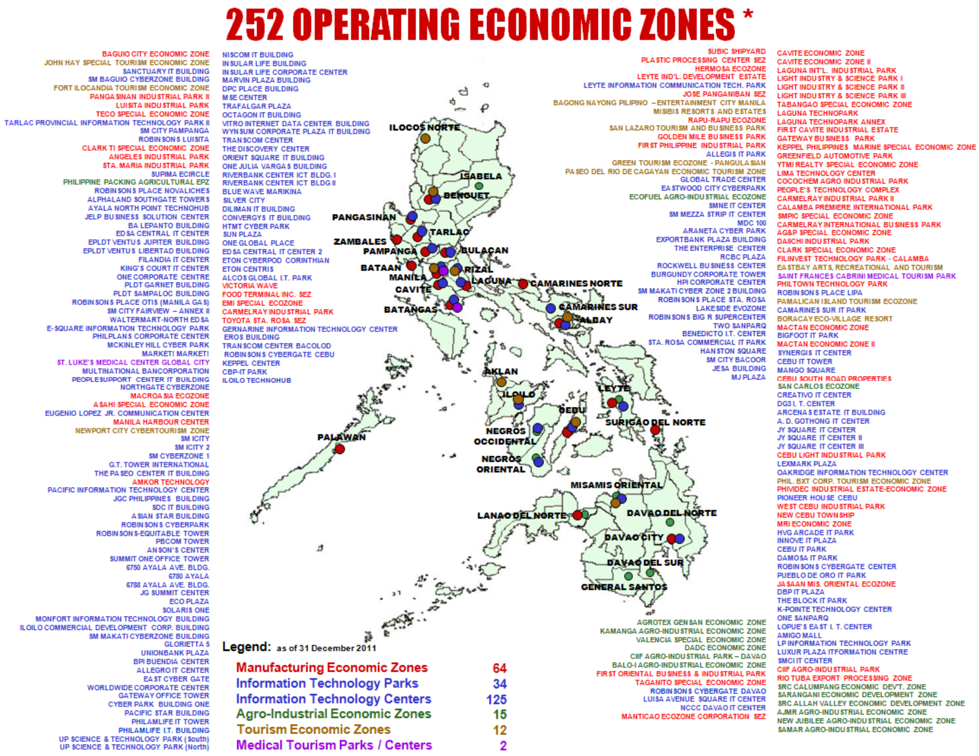


Figure 1. Philippine Map Showing the 252 Operating Ecozones

3. SYSTEM OVERVIEW

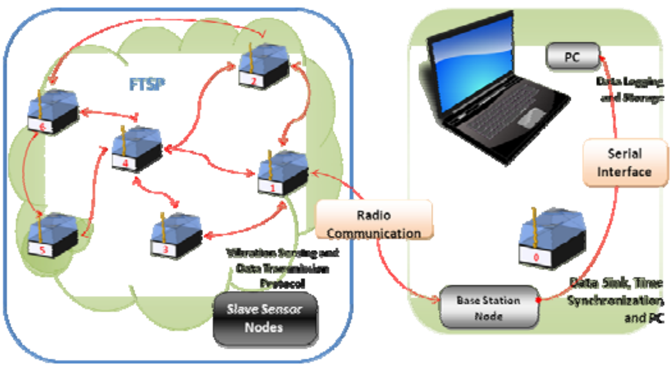


Figure 2. System Overview of wVIBES

The system is composed of six sensor nodes and one root/base station node. The root/base station node is responsible for receiving the data wirelessly from the sensor nodes and for passing it onto the PC, via serial interface, for data storage and for data analysis. All the global clocks of the sensor nodes should synchronize with the local clock of the root/base station node, thereby achieving network wide time synchronization. The system is flexible under the insertion and the removal of sensor nodes in the range of the wireless sensor network. Figure 2 shows schematically the system overview of wVIBES.

4. METHODOLOGY

4.1 Sensor Nodes

4.1.1 Custom Board Design

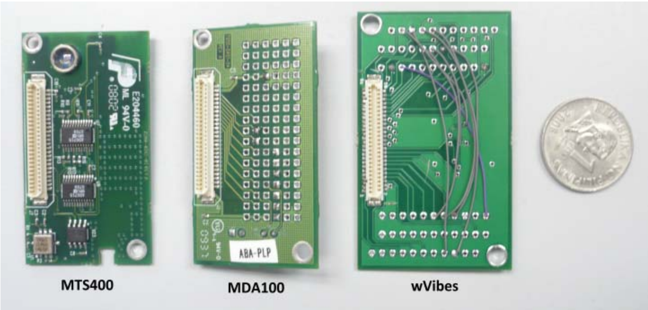


Figure 3. Sensor Node with other Commercially Available Sensor Boards

A single sensor node has two main parts, the platform and the sensor board. The platform is the commercially available MICAz mote that contains the ATMega128L microcontroller and the CC2420 radio chip. The sensor board, which is custom-designed, houses the tri-axial MEMS accelerometer that senses vibrations on three orthogonal directions. The output of the sensor is interfaced to the microcontroller through the analog-to-digital conversion (ADC) pins. Depending on the value of the sensed data, digitized by the microcontroller, the sensor node either ignores the data, if the sensed data is below the desired threshold, or sends the data to the base station for further processing, if the data exceeds the pre-defined threshold.

The sensor, the tri-axial MEMS accelerometer called LIS344ALH, is placed on the custom-made sensor board. To connect the output lines of the sensor with the ADC interface exposed from the board connector, additional signal conditioning circuitry is implemented as hinted from the LIS344ALH datasheet. Bypass capacitors are incorporated in the initial board design to improve the sensor's performance and as a design practice. Setting the bandwidth to 500 Hz, the bypass capacitors Cload x, y and z, as seen on Figure 4, are computed to be 3 nF each.

$$Bandwidth = \frac{1}{2\Pi x 110 k\Omega x C_{LOAD}} \tag{4.1}$$

The board has a buffer amplifier, the LM324 quad operational amplifier IC, to mitigate the loading effect brought by connecting the output pins of the accelerometer to the ADC ports of the MICAz platform.

The sensor board must have the necessary connector to connect all 51 exposed interfaces from the mote platform MICAz to the sensor board, with emphasis on the ADC lines. For the initial board layout sent for fabrication, the initial schematic diagram is designed. The accelerometer as well as additional components, as discussed earlier from interfacing the sensor to the sensor board, included the buffer amplifier, the bypass capacitors and the load capacitors, and that they are placed in the sensor board. The 51-pin Hirose connector is utilized to connect the sensor board easily to the MICAz platform that supports the same Hirose connector type. The board also exposes other microcontroller pins through pin holes, the prototyping area, for future development and for debugging purposes of the sensor board. The board measures 1.5 in x 2.5 in.

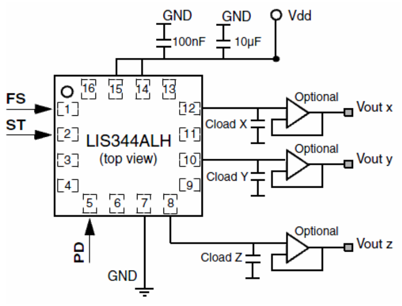


Figure 4. LIS344ALH signal conditioning

Table 4.1 Initial Accelerometer Testing with a Microcontroller

Initial Testing for LIS344ALH Test Board		
Axis	Before Connection	After Connection
X	1.65V (0 g)	1.45V (0 g)
Y	1.65V (0g)	1.45V (0 g)
Z	2.3V (1 g)	2.1V (1 g)

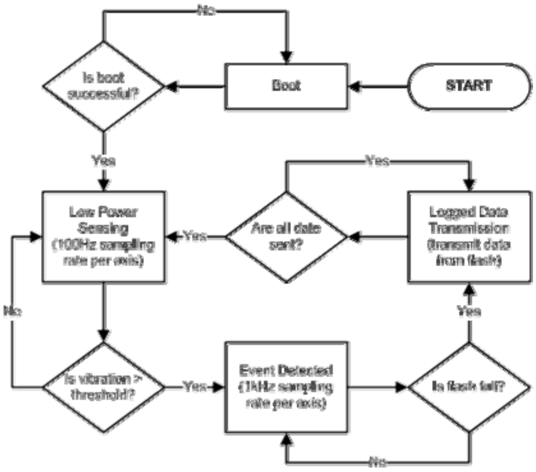
4.1.2 Firmware

The operation diagram of the slave sensor node is summarized in Figure 5. The state of the sensor node upon initialization is the boot state. After successful booting, it proceeds to low power sensing state wherein the ADC samples at a lower rate than required. There is no transmission of data from the slave node to the base station during this state. This is implemented to conserve the power of the sensor node by prohibiting the radio to transmit any messages when no essential data is acquired.

An event detection threshold is arbitrarily set to distinguish the minimum threshold vibrations from the desired vibrations. The value is arbitrarily selected because of few references to attribute the threshold to. The event detected state handles the operation of the sensor node when the sensed data exceeds the pre-defined threshold. The sensor node at this state triggers the microcontroller to sample the accelerometer at 1000 Hz per axis, and to start the data window for the detected vibration. The data window can be set up to 1 minute and 20 seconds at most (corresponding to 80,000 sampled data per axis, or a total of 240,000 sampled data). The sampled data are logged to the sensor node's Flash memory, the AT45DB011B, periodically while sampling. After sampling and logging, the sensor node enters the logged data transmission phase wherein the sampled data are wirelessly transmitted to a specified base station governed and managed by the system network.

4.1.3 Results and Analysis

Shown in Figure 6 is the result of the firmware when a sensor node is fed with a 10Hz sinusoidal signal and the signal is sampled for ten seconds. The reconstructed waveform shows the 10 Hz sinusoid. However, a drift has been detected periodically and it happens during the instance that the Flash logging is called during sampling. The CSV file verified that for a ten-second sampling, more than 10,000 samples for three channels have been achieved, for a total of more than 30,000 samples in all 3 axes. Another test is done wherein the sensor node is mounted to a cantilever beam shown in figure 7 and the beam is tapped. The sensed vibration induced by this tap is recorded by the sensor node for ten seconds and is transmitted wirelessly to the base station. Shown in the figure 8 is the received waveform from this test.



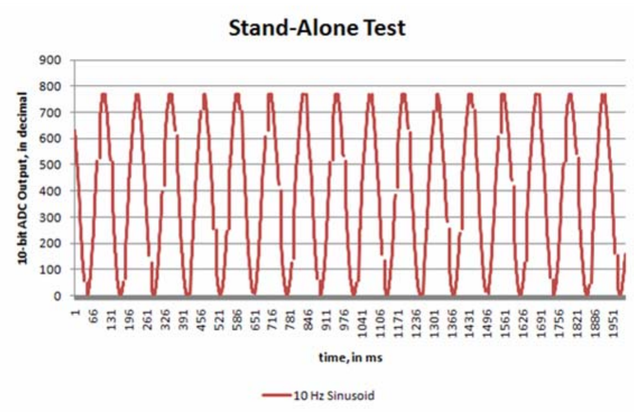
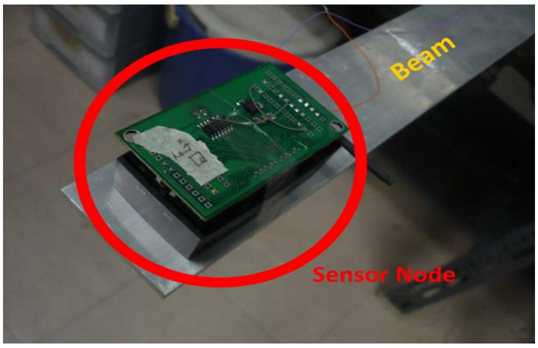


Figure 5. Slave Node Operation Diagram

Figure 6. Reconstructed Waveform from the Sampling Test



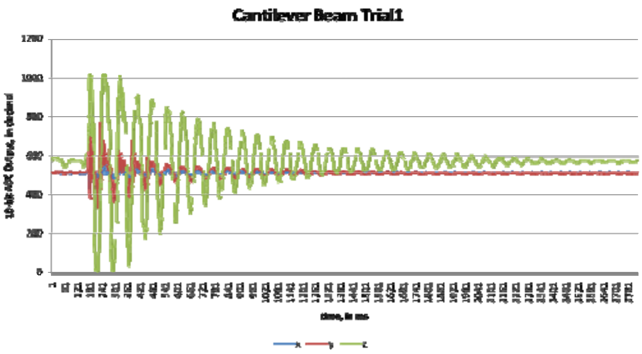


Figure 7. Cantilever Beam Set-up

Figure 8. Reconstructed Waveform from Cantilever Beam Test

4.2 System Network

All six nodes are used to represent a wireless sensor network that detects vibration data, and sends this information to the base station, wherein the message is stored in a data logger for further data processing.

4.2.1 Design Application

Each sensor node is programmed to send periodic synchronization messages so that all of the sensor nodes' global clocks are synchronized with the reference clock of the root/base station node. Aside from sending synchronization messages, tri-axial accelerometer values are sent for every event sensed by that particular sending node. A multi-hop protocol is implemented to minimize power consumption, but at the same time, provide a reliable transmission of data to the base station node.

CC2420 Radio Stack

CC2420 Radio's hardware is built to accept IEEE802.15.4 frame headers and that most of the data-link layer protocols implemented for this radio uses the said frame format. The CC2420 radio stack is composed of several layers that are virtually placed on top of each other that functions as a whole, more specifically, to process incoming and outgoing messages. A 2-byte CRC byte is appended to the outgoing message aside from the header field and the data field. The ideal maximum packet size is calculated by adding up the 12-byte CC2420 header field, the 114-byte data field, and the 2-byte CRC, giving a value of 128 bytes is obtained and this represents the maximum allowable packet size for the 802.15.4 standard.

According to the datasheet of the CC2420 radio, it is said that the maximum data rate of the radio is around 250kbps. Unfortunately, after testing on how fast the actual data rate can be, it is found out that it can only achieve a data rate of around 146kbps. The reason behind this is that there is an inherent transmission delay when sending a message. Transmission delay or transmission time is considered to be the time interval between the Send event and the SendDone event handler. For every transmission of packets, the radio encrypts the data field before appending the 12-byte header and the 2-byte CRC. In fact, the CC2420 radio uses the AES-128 encryption. This transmission delay is not proportional to the size of the packet. This means that whether a packet is sent with maximum data payload length or a smaller sized packet, the transmission delay falls close in value with each other.

Measurements of the transmission delay for variable packet sizes are tried. It is found out that there is a random value of 7msec to 15msec of transmission delay. This randomness is also observed by another TinyOS user in the forums and stated that he observed a randomness of 7msec to 10msec. This randomness is attributed to the encryption table re-writing at certain intervals. When the CC2420 re-writes its encryption table to reset the offset that the security pointer requires, a slightly higher transmission delay occurs. However, the ideal data rate is still achieved if the data payload length is increased beyond that of the IEEE802.15.4 standard, with the increase of RAM usage as well. To test this, measurements of the transmission delay is taken when sending a payload length that exceeds the 114-byte restriction, more specifically a 200-byte data payload, and a transmission delay of the same range as above, the 7msec to 15msec range, is obtained. This concludes that the data rate close to the ideal can be achieved, but a departure from the IEEE802.15.4 standard occurs, and therefore, is not processed by the CC2420 radio at the receiving end.

4.2.2 Implementation

a.) Flooding Time synchronization Protocol

Root Node Election

Since global synchronization is targeted, only one root/base station node should exist in the network hierarchy. FTSP is capable of providing an election process whenever the system is booted to start or when node failures occur during the operation. The motivation for this implementation is that monitoring real-world parameters leads to uncertainties in terms of natural occurrences that can affect the sensor network system by causing nodes to fail. Therefore, there should be no dedicated root node because if this dedicated root node fails in operation, then the whole system is paralyzed.

Reduction of Redundant Information

Given a massive wireless sensor network, different nodes are sure to receive different messages of the same type in very short intervals. Therefore, a reduction in message transmission is necessary so that packet collision and power consumption can be minimized. The concept is that for every node in the network, each of them stores a value of the highest sequence number they have received, and the corresponding root/base station node ID number that they synchronize their clocks with. Using these two parameters, the sending node and the receiving node can reduce message overhead, and thus reduce channel traffic, targeting reduced packet collisions, and especially reducing power consumption.

Clock Offset Prediction for Precise Synchronization

Broadcasting time synchronization messages is not sufficient to provide a highly precise synchronized network. Since clock frequencies between different sensor nodes are not the same, clock offset occurs inevitably. A solution to this hardware limitation is to let the nodes predict the clock offset needed to adjust their local clocks and be synchronized with the whole network.

This prediction can be accurately done by implementing linear regression. The main procedure here is that only the root/base station node can transmit time synchronization messages instantly. For a non-root/base station node to transmit a time synchronization message, that node should have a respectable number of reference points so that its prediction is as near as that of the root/base station node’s global time stamp.

Self-Healing Property of the Sensor Network and the Multi-Hop Protocol

Inclusion and removal of sensor nodes in the network hierarchy would not cause significant changes in performance since the implementation of a multi-hop protocol is done. If nodes are down, then other neighboring nodes can forward the messages of those nodes that are out-of-range from the base station node. If nodes are inserted to the network hierarchy, it can either act as a bridge that forwards messages to the base station node, or it can just be an ordinary sensor node that sends tri-axial data to the base station.

b.) Collection Tree Protocol

Suppression of Duplicated Data

A usual setup of wireless sensor network is that sensor nodes are scattered across the entire area and are communicating with more than one other sensor node so that data can be passed onto the root/base station node. There are cases wherein duplicated data is seen from the logged data at the base station end. One reason for this is that multiple nodes are hearing from a sending node and are forwarding more instances of the same message to the root/base station node.

The importance of using the collection tree protocol emerges from this situation. The collection tree protocol is an address-free sending of data wherein a sending node can send to different parent nodes depending on whose link quality is better. Only the estimated next best hop node receives a message from the sending node until it reaches the base station node.

Acknowledgement Packet

To be able to provide a reliable delivery of data from a massive density of sensor nodes to only one root/base station node, a certain type of detection is needed to indicate if the transmitted message is actually received by a receiver and has not collided with the other messages being transmitted over the radio. The simplest way of knowing if a communication link has been achieved between any two pair of nodes is to provide bi-directional communication between the two nodes.

In the case of the collection tree protocol, when a sending node transmits its message to a particular parent node, this parent node replies with an acknowledgement packet to indicate that the data has been successfully received. Once the acknowledgement packet has been received by the sending node, then it can continue transmitting other data stored up in its send queue. For situations wherein no acknowledgement packet is received by the sending node, then a retransmission process takes place where the message may be sent to another parent node due to link quality assessment.

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

When retransmission is necessary to resend data from different sensor nodes, a specific Medium Access Control (MAC) layer protocol is used to minimize the occurrence of another packet collision right after retransmitting a packet. The chosen protocol was the 1-persistent CSMA/CA since CSMA has been supported by TinyOS users for its high probability of data reliability. Because of this protocol, minimization of the probability of having consecutive packet collisions is achieved since even if several nodes simultaneously requested for a retransmission, the random timer provides a high probability for the sending nodes not to access the network at the same time.

Loop Detection

Since the collection tree protocol (CTP) uses an address-free type of sending messages, then there is a probability that a routing loop may occur. This happens when data is being passed around between a child node and a parent node. To tackle this issue of loop detection, a counter variable is used to indicate if a loop has occurred. Basically, this counter variable counts the number of times it is transmitted and if it crosses a certain threshold, it signals the node that a loop has occurred.

c.) Testing

According to Maróti et al. 2004, the most tedious scenario are the cases when: (1) the root node is removed from the network, (2) multiple nodes are removed from the network, and when (3) multiple nodes are inserted to the network. Knowing all these cases, the system underwent all these situations and an observation is done on the behavior of the system while determining its performance.

Testing for Synchronization of the Sensor Network

The following are the steps taken to test the efficiency of the time synchronization protocol:

Setup 6 sensor nodes that are arranged in such a way that the farthest sensor node, with respect to the base station, cannot send a single-hop transmission to the base station node. Turn on all the sensor nodes including the base station node and start the data logger application. Plot the collected timestamps versus time, and observe the behavior of the network in terms of time synchronization. If in the long run, the different plots from different sensor nodes coincide with the plot of the base station node, then that shows that the time synchronization protocol is sufficient to provide network-wide time synchronization.

After which, the limits of this time synchronization protocol is tested by removing 3 sensor nodes from the sensor network, thereby introducing a 50% node failure scenario. Afterwards, check the plots of the individual sensor nodes whether they coincide with the plot of the base station node. If they do, this proves the capability of the time synchronization protocol even under the situation of node failures.

Afterwards, turn on the 3 previously removed sensor nodes, thereby introducing a 100% inclusion of sensor nodes, and check the plots of the individual sensor nodes whether they coincide with the plot of the base station node. If they do, this proves the capability of the time synchronization protocol under the situation of node inclusions.

For the case of using the <T32khz> precision tag, the conversion factor is 32768 clock ticks per second. Using this information, the synchronization error in terms of time can be computed. The table below shows the maximum synchronization error occurring between any 2 pair of nodes for a unique reference counter value. The test setup is such that the nodes are placed quite close to each other, each of which are turned ON at different times, and the experiment lasted for 5 minutes. Also note that a one second synchronization interval is used for the whole experiment.

Table 4.2 Synchronization Error

Number of Nodes	Synchronization Error (in clock ticks)	Synchronization Error (in seconds)
2-Nodes	4 clock ticks	122 usec
3-Nodes	8 clock ticks	244 usec
4-Node	8 clock ticks	244 usec
5-Node	7 clock ticks	213.6 usec
6-Node	7 clock ticks	213.6 usec
7-Node	8 clock ticks	244 usec

Testing for Multi-Hop Data Transmission

After checking the performance of the time synchronization protocol, the reliability of data transmission from a sending node to a destination node is tested. Integrating both the Flooding Time Synchronization Protocol and the Collection Tree Protocol onto each of the sensor nodes is done, with different tests/experiments conducted to measure the capabilities of the wireless network implementation. The most important test is to see if a signal sampled by all the sensor nodes in the network can be reconstructed in a way that when data is plotted at the root/base station node, the waveforms from all the sensor nodes are aligned even though the sensor nodes are turned ON at different times, and noting that some of the sensor nodes are in a more-than-one-hop distance from the root/base station node, thereby testing the multi-hop capability of the system. Figure 9 shows the results of such an experiment. From the figure, the waveforms from the data, as sent by the sensor nodes, are aligned and shows that the network-wide time synchronization is achieved. Data from far-away nodes are also successfully received by the root/base station node through the use of the CTP.

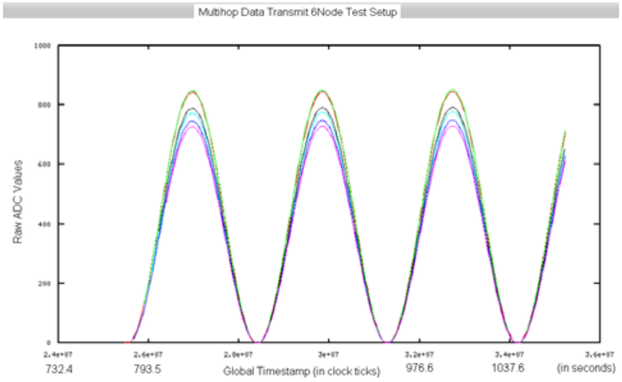


Figure 9. 6-Node Multihop FTSP and CTP

5. CONCLUSIONS

This research produced six custom sensor boards for vibration sensing, develop a data logger which gathers the acquired raw data from multiple nodes to a CSV file, implement a network-wide time synchronization with a millisecond precision using the multi-hop flooding time synchronization protocol, and deliver data reliably regardless of transmission range using the collection tree protocol. Six sensor boards were used. The LIS344ALH tri-axial accelerometer, contained on each sensor board, was made to sample at the rate of 1000 Hz, for each axis so that the system will be able to detect transient vibrations from highly-damped structures that have the tendency to respond with an exponentially decaying vibration response. Millisecond-precision network-wide time synchronization for the sensor network was attained using the Flooding Time Synchronization Protocol. Using this protocol, multi-hop time synchronization can be achieved, and therefore, the transmission range of the root/base station node should not be a factor in terms of time synchronization of the whole sensor network. Lastly, implementation of a reliable data delivery using the Collection Tree Protocol that focuses on the Medium Access Layer Protocol known as the 1-persistent Carrier Sense Multiple Access with Collision Avoidance was developed. From the experiments conducted, a minimum of 98% successful data delivery can be achieved, using the implemented protocol, regardless of the transmission range of the sending and the destination nodes. The total cost of the system (6 nodes + base station node + laptop PC) is only US$1,400, making it affordable for developing countries to implement. The system is ready for testing using simulated earthquakes on a shaking table.

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