DEVELOPMENT OF LOW COST ONLINE STRUCTURAL HEALTH MONITORING SYSTEM FOR CIVIL INFRASTRUCTURES USING WIRELESS SMART SENSORS

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Degree of Master of Science

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Thesis submitted in partial fulfilment of the requirements for the degree
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DECLARATION

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Signature of the supervisor: ……………. Date: …………………………

ABSTRACT

Over the last few decades number of tall buildings has seen an exponential increase. At present tallest ever building under construction measures 1000m vertically, and the height of future buildings is likely to be even higher. Monitoring the behaviour of tall buildings using them as living laboratory is extraordinarily important in an international context to optimize its performance. Structural health monitoring is a new paradigm which facilitates the purpose of monitoring buildings or any other infrastructure on real time basis. Structural health monitoring has seen various advanced developments in recent past. Wired sensor networks were used to monitor the target at the beginning. In modern days wireless network with higher number of nodes is used to monitor the target very precisely.

In this research a wireless sensor network which is capable of sensing ambient vibrations in terms of accelerations was developed. The sensors mounted in each node are capable of measuring very small vibrations (1 mg range). The communication between each node was established using wireless network protocol, sub-1 GHz (Radio waves) which is very efficient in terms of long-range communications, power consumption and penetration through obstacles. When it comes to collecting data using wireless sensor networks, there are inherent challenges such as time synchronisation, scalability, packet handling (collision), packet loss, data storage, power consumption etc. However, accuracy of time synchronisation was identified to be the most crucial problem as far as interpretation of results is concerned. Two methods of time synchronization were checked in laboratory level. One method is known as receiver to receiver model and other one is centre to receiver model. Wireless sensor network was checked for its performance in laboratory level and accelerometers were calibrated using shaker table which has accurate analog sensors and digital accelerometers which are already calibrated in laboratory level.

Completely developed wireless sensor network which is capable of collecting synchronous data, was established in a target building of 48 floors with 185m height. The locations of sensors were predetermined using mathematical model made using finite element package, ETABS. Bi directional acceleration data was collected with sampling frequency of 100 Hz. Collected data was chunked and converted into frequency domain from time domain using fast Fourier transform algorithm and modal damping ratios, peak acceleration corresponding to particular frequency and modal displacement were extracted.

Extracted modal damping ratios were compared with the damping ratios suggested in various codes and it could be observed that the calculated modal damping ratios are higher than the values that are suggested by various codes. The mode shapes plotted using the building response data showed a good agreement with the mode shapes produced by Operational Modal Analysis.

Keywords: Ambient vibrations, low cost accelerometers, Tall buildings, Wireless sensor network, Time synchronization, Cascading effect, Inundation area, Compensations, Damage prediction, Real time monitoring, Structural health monitoring.

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Punithavel Vishnu.

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LIST OF ABBREVIATIONS

SHM	Structural Health Monitoring
MAC	Modal Assurance Criteria
FEMA	Federal Emergency Management Agency
UDA	Urban Development Authority
IoT	Internet of Things
NB-IoT	Narrow Band Internet of Things
WSN	Wireless Sensor Networks
WMS	Wireless Monitoring System
PCB	Printed Circuit Board
SN	Sensor Node
CH	Cluster Head
MN	Master Node
ALU	Arithmetic Logic Unit
OMA	Operational Modal Analysis
FFT	Fast Fourier Transform
MEMS	Micro Electro Mechanical Systems
ISM	Industrial, Scientific and Medical
MEMS	Micro electro mechanical systems
ADC	Analog to digital converter
RTOS	Real Time Operating System
PP	Peak Picking

MAC	Modal Assurance Criteria
MAC	Media Access Control
WSN	Wireless Sensor Network
PAN	Personal Area Network
MEMS	Micro Electro Mechanical Systems
RoHS	Restriction of Hazardous Substance directive
I^2C	Inter Integrated Circuits
SDA	Serial Data
SCL	Serial Clock
SPI	Serial Peripheral Interface
MOSI	Master Out Serial In
MISO	Master In Slave Out
SS	Slave Select
UART	Universal Asynchronous Receiver and Transmitter
MPLS	Multi Protocol Label Switching
GSM	Global System for Mobile Communications
GSA	Geographical Service Area
BSC	Base Station Controller
NSS	Network Sub System
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Services
SMS	Short Message Service
VoIP	Voice over Internet Protocol

LPWAN	Low Power Wide Area Network
XML	Extended Mark-up Language
SGML	Standard Generalized Mark-up Language
SQL	Structured Query Language
DDL	Data Definition Language
NoSQL	Not only SQL
HTTP	Hyper Text Transfer Protocol
HTTPS	Hyper Text Transfer Protocol Secure
HTML	Hyper Text Mark-up Language
CSS	Cascading Style Sheets
JS	JavaScript
SNR	Signal to Noise Ratio
OS	Operating System

CHAPTER I

1. BACKGROUND

1.1 Introduction

The number of high scrapers constructed in last few decades has increased exponentially. With the introduction of modern high strength materials and new construction technologies, latest tendencies of high-rise buildings have become slender and the heights of new buildings even exceed 1km.One of the key features of the tall buildings is the behaviour as a cantilever with a substantial fixity at the ground level. Hence, when the number of floors are high, the building tend to move in elliptical fashion due to the wind induced forces of various magnitudes. However, one of the important aspects is that these movements cannot be prevented, but can be controlled only to a certain extent.

In high-rise buildings, efficient space planning and optimization in the upper part of the building would need special elements such as transfer floor or large transfer beams. Hence, the structural arrangements used in the tall buildings can differ substantially from typical buildings thus warranting a detailed study involving the measurements taken in real buildings with typical structural forms peculiar to location of interest. This situation is further reinforced with the introduction of pre-stressed concrete flat plates in many commercial and apartment buildings of recent origin thus adding further unknown parameters.

If a tall building is constructed with adverse wind induced accelerations, there is a possibility of rendering the top most floors of the building being not occupied and Traditionally buildings are designed using higher loads due to lack of past data of similar type of building. The loads used are either higher leading to disastrous wastage of structural material (including carbon and cost) or lower which is catastrophic.

Monitoring existing building will produce ample of data such that collected data can be fused in real time and fundamental knowledge for better design can be extracted.

Coupled with this it is necessary to understand, how the wellbeing and productivity of users of tall buildings are affected by structural behaviour of such buildings, due to vibration and sway.

1.2 Problem identification

Since the paucity of data of similar type of buildings, leads design community to use higher loads which paves the way to over design, it is necessary to monitor the structures keeping them as living laboratory, in order to record the response of the existing structures which can be used as a guide for optimized design in future. Complication level of monitoring of building response, depends on the parameter monitored and various other facts related to the system that monitors the response and the structure being monitored.

1.2.1 Structural Health Monitoring (SHM)

Structural health monitoring is an emerging field that monitors various parameters of the structure at various parts of the structure, using various technologies, throughout the life span of the structure. It facilitates the collection of response data of the structure. It also helps the stake holder to have a proper idea of structure's health during its life time and damage prognosis. Damage prognosis not only can save many lives, it also can save a lot of money that is spent on repairing structures. SHM not only facilitates damage prognosis, it also helps designer to make sure that the real behaviour of structure remains in the domain specified during design stage.

Structural Health Monitoring is applicable to any field starting from small motors to Supertall buildings and space applications. A bridge that connects health of civil engineering structures and SHM needs to be properly established.

1.2.2 Monitoring the structures with low cost involved

Even though SHM is a non-destructive evaluation method, it involves cost that can sometimes not affordable by design community in developing countries, sometimes even in developed countries. In early ages, structures were monitored by visual inspection where the stake holder must present at site in order to monitor the structure. Since visual inspection method is labour intensive, it was considered to be in efficient method, and also this method doesn’t guarantee that the structure is fully monitored and damages are properly identified.

With the introduction of modern electronics and the accidents in aeronautic field and civil engineering field, that cost several million of money, SHM was considered to be a field that is mandatory and need to be a part of the structure throughout the structure’s life span. Lack of maintenance of any structure can be detrimental than design failures, because it is almost impossible to incorporate all the loads and scenarios during the design stage itself. This is the point where the design community tend to estimate the loads that are very high thus end up having a structure over designed with lot of money and carbon foot print involved.

The money that is spent on additional/overestimated safety measures taken at the very early age can be cut down and portion of this can be used for SHM throughout the life span of the structure which not only reduces the overall cost and it is very much reliable due to its capability of damage identification at very early stage.

The SHM method now has evolved in many different ways from methods that were used in early stages. Nowadays with the introduction of Internet of Things (IoT) Wireless Sensor Networks (WSN) has become popular. IoT is nothing but an extension of internet into physical devices/sensors. It is widely used worldwide due to the increasing popularity of smart home concept.

The application of WSN in structural health monitoring has many attractive aspects as well as difficult challenges. These challenges need to be addressed in order to have a low cost efficient SHM system.

1.2.3 Monitoring structural response

Structural response can be compared to human response to the senses. This analogy gives a clear idea of the importance of knowing what to monitor in order to come up with meaningful outcome. Typical parameters monitored are accelerations, deflections, strains, wind speed, temperature, humidity, radio activity, corrosion level, pH etc.

1.2.4 Importance of monitoring acceleration

When it comes to high rise buildings, the dynamic characteristics such as natural frequencies, mode shapes and modal damping ratio of the building plays a pivotal role in seismic design. By monitoring acceleration only, all of these parameters can be extracted. In addition to design benefits, accelerations measured in the building is a good indicator of comfort level of people, accommodate the building. In this research the acceleration response of a target building was monitored by establishing WSN in a target building.

1.3 Objectives of the study

Following main objectives are tried to be achieved during this research

1. To develop low cost structural health monitoring system which is capable of sensing very low range vibrations (in mg range) and save the data in the webserver (data sink). This monitoring system can collect data at higher rates (100 Hz) which is suitable for monitoring most of the civil engineering structures.

2. To monitor a target building using this SHM system developed, as a case study and predict mode shapes and modal damping ratios of the building at various modal frequencies. The modal parameters calculated will be checked with the results obtained using mathematical modal.

These objectives were set based upon the literature review done so far and consulting peer researchers from various disciplines who are also involved in these kinds of research.

It could be understood that these kinds of researches are rare and there is no such SHM system has ever been developed in Sri Lanka for monitoring civil engineering structures. Data base of past modal characteristics of real buildings constructed in Sri Lankan context, is an urgent need in order to use as a guide for future designs. In order to achieve the set objectives following methodology was used.

1.4 Outcomes

- A low-cost wireless sensor network that is capable of capturing acceleration response at higher frequency (100 Hz). The data collected is synchronous and can be used for extracting modal response of the structure and asses the comfort level.
- The developed system can capture the data with acceptable time synchronization error (less than 120 µs). In addition to that, the system developed is scalable due to the synchronized sensing method, where the system is capable of adapting itself to the new number of nodes. This is achieved by having multiple hops while keeping the error within 120 µs (i.e. the error doesn't propagate.)
- A database of modal responses such as modal frequencies, Modal damping ratios, and mode shapes etc. for a target building is has been created. This is achieved by online repository system and back end analysing algorithms.
- A complete case study of a high-rise building establishing wireless sensor networks in order to capture synchronised acceleration response history, hasn't yet been done in Sri Lanka before. This case study will serve as a complete guide to monitor a civil structure with low cost involved.
- It was found that the damping ratios that are suggested in current design codes need to be revised incorporating height and shape of the building. The damping ratios have to be suggested for each significant mode. The target building showed very good damping characteristics. The modal damping ratios were higher than the values suggested by various codes even at the uncracked stage

1.5 Structure of the thesis

The arrangement of the chapters of this thesis is made such that, it is aligned with the methodology of the research. This thesis consists of **7 chapters.** Literature review is done in each chapter except **Chapter 1** along with the flow of the thesis. This thesis has main two parts where one part mainly discusses about the development of low cost online structural system and other part discusses about the applications of the data collected, analysis and conclusion.

Chapter 1 gives introduction to the research and walks the reader through the thesis at a glance. It gives the overall idea of the research starting from problem identification to methodology of the research.

Chapter 2 introduces Structural Health Monitoring, IoT applications and Wireless Sensor Network and its growth. It also discusses the how sensor nodes work generally and the data flow through, starting from sensor node to the data sink (The storage of data) and it reviews the past work done so far in structural health monitoring. Finally it discusses the key features and how this field has evolved from beginning. Applications of wireless sensor network in building and bridges are mainly discussed due to its relevance to this scope. The applications of the data gathered also discussed for the sake of relevance.

Chapter 3 Discusses the development of wireless sensor network developed under this research and its competence with other systems used worldwide. It explains everything from scratch, starting from sensor, establishment of wireless communication and time synchronization which is the most crucial part when it comes to wireless sensor networks.

Chapter 4 Explains the later part of the data flow. It explains how data is transmitted from gateway of the wireless sensor network to server. It compares GSM with NBIoT telecommunication protocols. It further illustrates the visualization and development process of web-based data logging.

Chapter 5 does a cost comparison by comparing the cost involved with this developed system, and normally available SHM systems. It discusses the advantage of developing these kinds of systems, and it also discusses further cost cutting methods in order to reduce cost per node. Cost reduction encourages to use more nodes and create dense arrays of sensor network which increases the accuracy of capturing building response

Chapter 6 Discusses about the building selected, mathematical model of the building, the locations of sensors and the acceleration data collected from the building. It also discusses the analysis of gathered data using Fourier transformation. In this chapter the results are also summarised and tabulated.

Chapter 7 includes the discussions, the decision based upon the results. It also includes the conclusions and recommendations for the future study.

CHAPTER II

2.0 LITERATURE REVIEW

2.1 Structural Health monitoring using wireless sensor networks

This chapter introduces Structural Health Monitoring and its evolvement from the beginning. In modern era with the “Global Village” concept, Internet of things have become popular even in developing countries. Effort of bringing that technology into Structural Health Monitoring, through Wireless Sensor Networks (WSN), is put by many researchers these days. This chapter introduces almost every aspect of it along with proper literature review.

2.2 Structural Health Monitoring Vs Human Health Monitoring

2.2.1 Human Monitoring

In recent past Human health monitoring using sensors, has become popular. In human health monitory systems, the clinical data of the patient is shared over the internet which is accessible by all the stake holders from the other end. Sensors which are flexible, small, weight less and low cost are mounted or inserted into the body of the patient in order to monitor the health parameters. By further processing of data and wireless transmission to internet (via smart phones mostly), the system can monitor the health in real time[1][2]. Wearable systems that are worn or mounted or inserted in various places of the body of the patient as shown Figure 2.1 monitors the health of the patient throughout the lifespan[3].

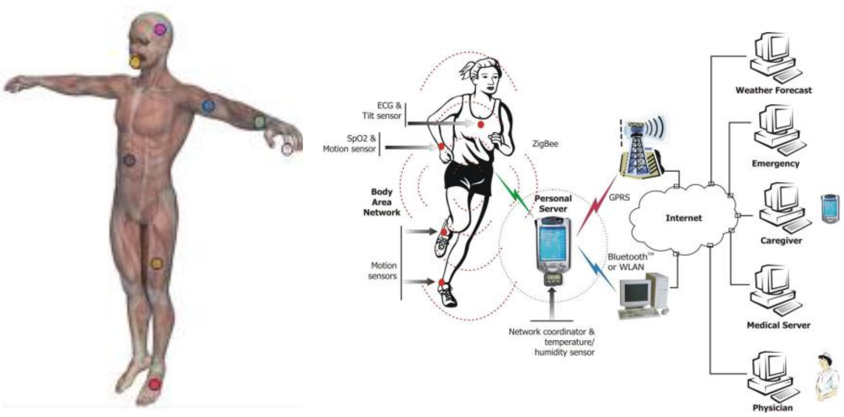
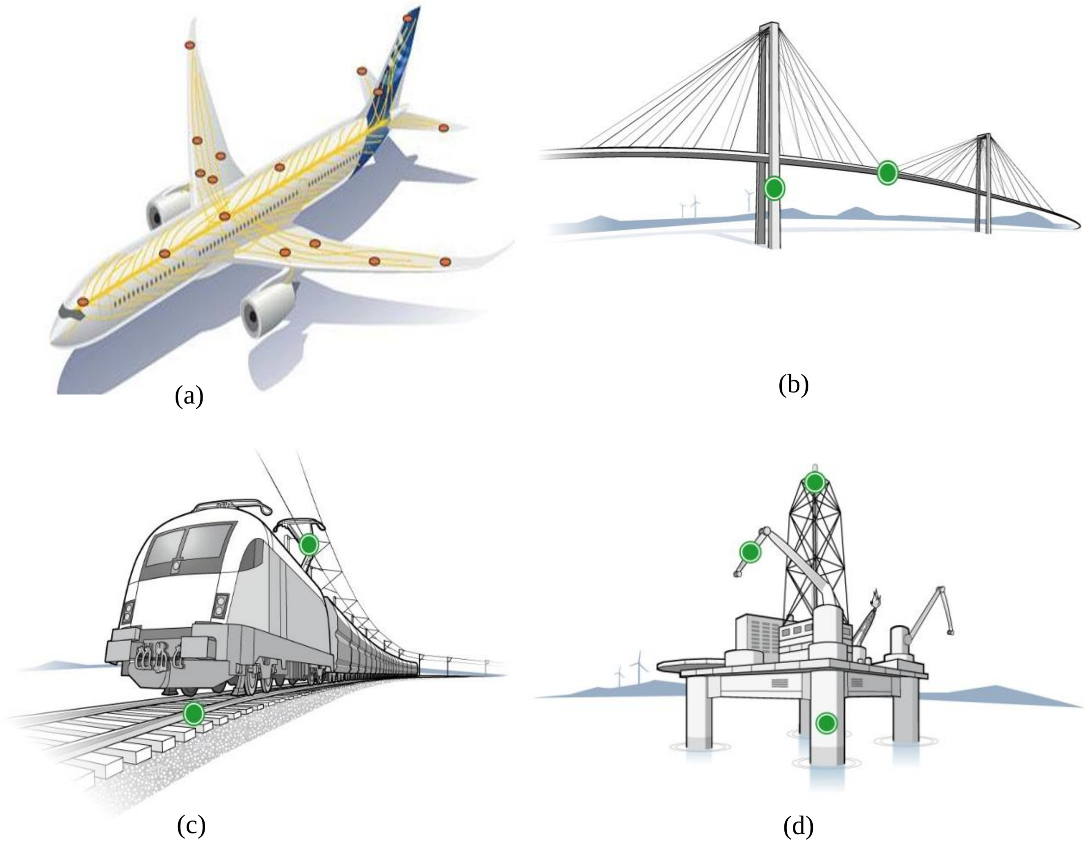


Figure 2.1. Locating sensors in human body and monitoring the health remotely. Source [1] and [2]

2.2.2 Structural Health Monitoring

Structural health monitoring can simply be defined as a process of identifying damage during service using automated monitoring systems. The word structure does not belong to civil engineering infra structures only, so as the word "Structural Health Monitoring" (SHM). SHM is crucial and plays a pivotal role in maintenance of structures which belong to other disciplines such as aeronautical, Mechanical, Robotics and many other fields[4][5].Figure 2.2 shows, applications of SHM in aeronautical and civil engineering fields.



(a) (b) (c) (d)

Figure 2.2.(a)Applications of SHM in aerospace applications, (b)Bridge monitoring using sensors,(c) applications of SHM in transport sectors (d) Oil rigs being monitored to prevent fatigue failures Source: Centre of applied research technology (Amsterdam University y of Applied Sciences) and HBM: Modular solution for efficient structural health monitoring, official website.

Development of SHM system requires a collaboration among many fields such as sensor networks, signal processing, damage diagnosis, tele communication, Structural engineering etc. Each and every discipline is a subject by itself. Contribution from each discipline is equally important in order to arrive at efficient SHM system.

Important benefits of monitoring a structure are mentioned below.

- Monitoring the structure gives early warnings of structural failure which helps the relevant people to rectify the problem before it becomes fatal.
- Damage prognosis is possible only by an efficient SHM, which not only identifies the problem, also it gives the idea of real behaviour of the structure opposed to the designed behaviour.
- SHM gives data sinks of ample amount of data of similar types of structures which leads to optimized and efficient designs of the structures in future. Optimized design of civil infra structures not only enhances public safety, it also lengthens the life span of the structure.
- SHM reduces the cost of the structure through optimized designs, thus contributes to the economic development of the country.

Table 2.1. Comparison between critical phases of man and the structure

Aspect of the life	Man	Structure
Beginning	Birth	Beginning of Construction/ End of Design stage
Health Inspection	Regular Health check up	**Structural Health Monitoring**
Defect identification	Diagnosis of Disease	Damage prognosis
Remedy	Clinical process	Damage rectification or evacuation of building for safety purpose
End	Death	Demolition or Collapse

Comparing Structural Health with Human Health will give a good idea how SHM functions and where the inspiration came from. Table 2.1 compares phases of Man and Structure in terms of three main aspects [6].

2.3 Wireless sensor networks and internet of things

Internet of things has now become very popular in the recent past after the introduction of concept of "Global village". IoT is a system which refers to wide range of area where almost all the things which are used in day to day life are interconnected via internet. It facilitates, controlling of any devices simply by using a phone/button in a remote manner. The complication on Internet of Things has attracted a lot of researches towards this field [6][7]. Figure 2.3 shows how internet of establish links between each other.

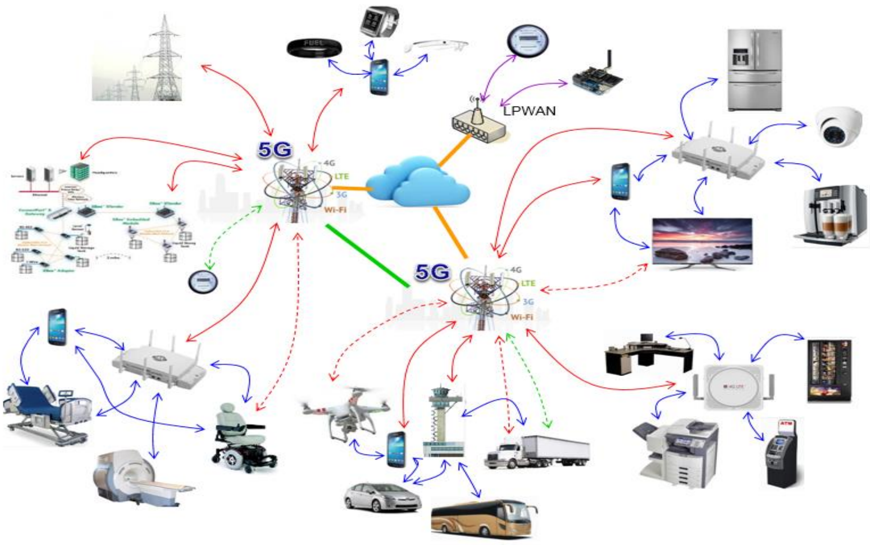


Figure 2.3. Schematic diagram of Internet of Things. Source: "Tech note" official website

Traditionally SHM was done by visual inspection at the beginning, where the structure was inspected manually in order to identify the damage. Then with the introduction sensor technology the human effort was lessen and long-term monitoring was possible. Initially the sensors were connected by wires, thus the system was known as wired monitoring system.

Recently wireless sensor networks (WSN) has become a new substitute for the traditional tethered monitoring system. Wireless sensor networks established in

Structures is a subset of IoT systems where accuracy required is high and the networking protocols that are used in order to establish sensor network should be able to transfer the data at higher rate compared to that of day to day IoT applications. With the introduction of new electronic systems with high processing power and remote sensing ability, wireless monitoring system (WMS) has become an attractive solution for SHM.

Traditional wired sensing methods are labour intensive due to its complicated arrangement of long wires, which is a major contributing factor for the higher cost involved. Wired sensing networks usually takes several days to deploy because, running of wires through structure without invasion of space is not an easy task. Since the cost is high in wired monitoring systems usually it consists of lesser number of nodes. However, wired sensor networks have higher band width (i.e higher data transfer rate) and good synchronicity among nodes due to its wired connection between nodes[8][9][10].

Wireless sensor Networks are less expensive and quick because of elimination of complicated wiring through the structure. It is suitable for both long term and short-term monitoring of the structure. Apart from its attractive features, WMS has inherent challenges which are currently overcome with the recent advances in electronics and telecommunication. Wireless sensing network has nodes, which consist of required sensors connected with computational platforms, and a wireless transmission component such as Wi-Fi module. These nodes generally run on battery power, which needs regular recharging, thus resulting in regular maintenance requirements. Wireless sensing network has lesser band width compared to wired method, but it does not have significant impact in data transfer because in SHM systems, data transfer rate requirements are lesser. Even with 16bits resolution of data with data acquisition frequency 1kz the data transfer rate would be 128Bytes/s.

$$\frac{1000\,samples}{second}\,x\,\frac{16\,bits}{sample}\,x\,\frac{8bits}{Byte} = 128Bytes/second \qquad (2.1)$$

In other words, it would only be 0.128kB/s whereas modern transmission wireless protocols can even transfer in a rate of 100 MB/s within small ranges. Another main challenge in wireless monitoring is synchronization of data, due to its connectivity over air, whereas wired monitoring systems are much more reliable as far as synchronization is concerned. SHM using Wireless Sensor Networks suits Civil engineering structures well, due to its easiness of handling and long-range transmission of data.

However, the success of WSN depends on the way it is connected with sensors, nature of sensors, electronic design, power supply, telecommunication protocol etc. The path in which the data travels defines the importance level of each component. Data flow starts from the sensor node and it ends up in the data sink. The flowing subheadings are expanded based upon the components through which the data travels.

2.4 The structure of wireless sensor network

Wireless Sensor Networks consist of two main components namely node and the gateway or sink. The Sensor Node (SN) is the starting point or the point where the response of the structure is captured. Wireless Sensor Network is established by connecting or linking several nodes using networking protocols such as Bluetooth, Wi-Fi, RF (Radio frequency), ZigBee etc. Nodes are connected to the Cluster Head (CH) using same protocols. Cluster head is nothing but a node which is the master of a cluster of sensors (A subset of the entire network of sensors). Cluster heads are responsible for establishing connection between peer cluster heads thus requiring a powerful networking protocol which has long range capabilities. Cluster heads are also responsible for back up the data collected by the cluster of sensor nodes for which it is responsible for, thus requiring higher storage capacity most of the time. Cluster heads are connected to Master Node (MN) which is the head of all cluster heads.MN is connected to gate way through suitable protocol. The gate way is the out let of the sensor network which links the WSN to internet through suitable telecommunication protocol (GSM/LoRa/NB-IoT). Gateway which is a router mostly, is connected to telecommunication tower using suitable telecommunication protocol (ex. GSM or NB IoT). The success of SHM using WSN is completely dependent upon the reliability of the network established. Figure 2.4 illustrates how the network is established using simple diagram.

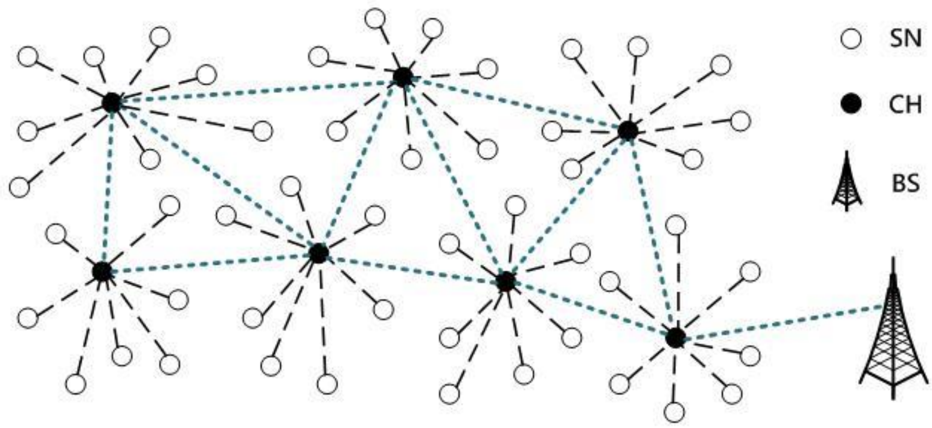


Figure 2.4. Hierarchy of Wireless Sensor Network. Source: eNewsletter issue#33

2.4.1 Sensor Node

Sensor node is wrongly understood for sensors by most of the people. In fact, sensor is a part of a sensor node. Sensor is just an electronic instrument that detects the state/ response of the system. Sensor nodes typically consist of 5 main components which are sensors, central unit or microprocessor, telecommunication module (Transceiver or receiver), Memory and the power supply or energy harvesting systems[11]. Figure 2.5 illustrates the architecture of a sensor node.

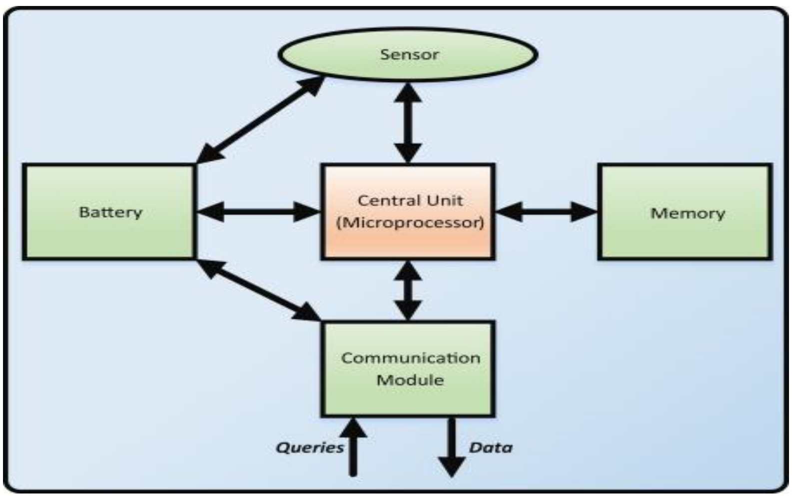


Figure 2.5. Architecture of a sensor node. Image is reproduced from [11]

2.4.2 Functionalities of sensor node

Sensor nodes has many functionalities out of which 6 functions are vital for a robust and reliable sensor network.

- **Analog to digital conversion**

When the sensors used are analog type, Analog to digital conversion needs to be done. The level of accuracy of the date is dependent upon this step.

- **Buffering the data**

When the there is a difference in between the amount of data collected and the data shared due to the wireless network sharing technology, there must be a memory which holds the data until the completion of the sharing process

- **Conversion of data into suitable format**

The data need to be converted into suitable format that suits for data sharing. For an example, sensors that use MQTT protocol need to covert the data into a type where the data is arranged such that control header (1Byte),packet length (1-4 bytes), Variable header and payload. This process is important to establish the connection between nodes, CHs and clients.

- **Establishing the network connection**

When the network is established there are many wireless networking protocols that can be used in order to achieve this task. Communications modules are instructed by the code running in the micro controller, to establish the connection. This process is important for a healthy cluster.

- **Time Synchronization**

Similar to all electronic devices there is a clock in sensor nodes used in SHM. Time synchronization is widely discussed in **chapter 3**. Time synchronization in micro level is required for civil engineering applications. This is achieved by sensor nodes over the air.

- **Sharing the data**

This is the final level of the data within the sensor node. The data collected is shared through wireless protocol. The sharing of data happens at all levels in WSN. (i.e. SN to SN, SN to CH, CH to Master node, Master node to gate way etc. As far as architecture of the sensor node is concerned, Sensor node, Cluster head and Master node are same. They differ from each other by the type of the feature used. For example, Sensor node might use radio frequency module for communication where cluster head might use Wi-Fi module for communication.

2.4.3 Wireless Technology Standards used for establishing the network

In this sub section the main aspect which makes the system wireless, is discussed. The data flow in any network whether it be wireless or wired/tethered, has same architecture. Components that makes the system are the main factors that makes the system different. Figure 2.6 show the typical data flow path starting from sensor to data logger. There are many Wireless communication technology standards such as Bluetooth, Wi Fi, ZigBee, Sub-1GHz etc.

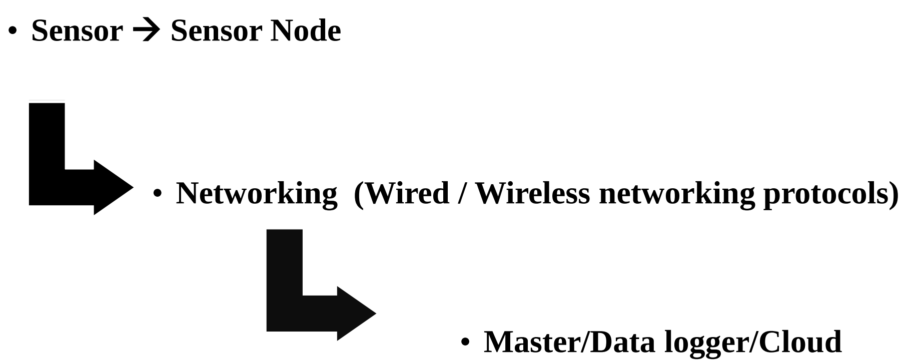


Figure 2.6. Data flow within a sensor network

Choosing of correct protocol is important in order to establish efficient network. Factors such as data transfer rate, distance between sensors, power consumption are the key points to be considered when choosing the network. Different protocols work at difference frequencies where data transfer rate is proportional to frequency of protocol. However, when higher the frequency of the protocol lesser the range would be. Range covered and data transfer rate can't be compensated for one another.

2.4.3.1.1 Bluetooth

Bluetooth is a wireless technology standard which is meant for transferring data over short distances. It operates on UHF radio waves. It is widely used in phone applications. It is not widely used in monitoring of civil engineering structures because of its low range (i.e 20 m range line of site) [12]–[14]. Figure 2.7 shows a typical Bluetooth module that is embedded in platforms in order to establish short term wireless communication. It can be seen in the picture that the copper line imprinted is the transceiver (Transmitter and receiver) which communicates with peer Bluetooth module.

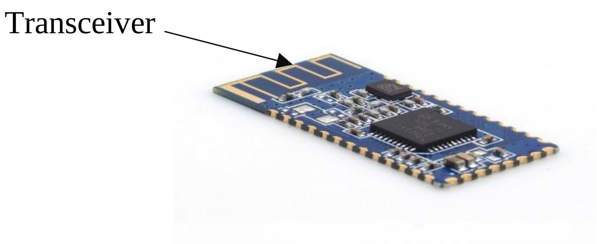


Figure 2.7. HM-10 CC2540 4.0 BLE Bluetooth UART transceiver

2.4.3.1.2 Wi-Fi

Wi-Fi is well known for local area networking of devices based on the IEEE 802.11 standards. The frequencies of operation of Wi-Fi are 2.4 GHz or 5 GHz. As far as coverage is concerned Wi-Fi is far better than bluetooth. Wi-Fi is preferred for IoT applications and it is even used in monitoring civil engineering structures, where the structure has Wi-Fi facilities and the sensor node is in the vicinity. Similar to Bluetooth, Wi-Fi is also used in short range monitoring applications (i.e. 50 m indoors)

[12]–[14]. It consumes 0.1W power at max. Figure 2.8 below shows ESP8266 Wi-Fi module which is widely used.

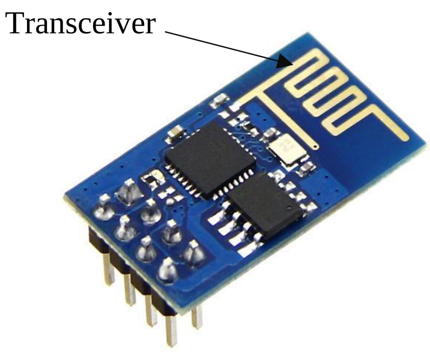


Figure 2.8. ESP8266 Wi-Fi module

2.4.3.1.3 ZigBee

ZigBee is used in most of the IoT applications and this is used in bridge monitoring worldwide. Zigbee is an IEEE 802.15.4-based specification which is used widely to establish local area networks. Main disadvantage of ZigBee is, it requires line of sight connection, in other words, it can be used only in low-latency communication.[15]–[17] ZigBee can cover 10-100 meters under low power consumption which enables ZigBee to be used in wireless personal area networks. ZigBee, Wi-Fi and Bluetooth, all operates in Industrial, Scientific and Medical (ISM) bands. ISM bands are nothing but radio bands reserved radio frequency (RF) for industrial, scientific and medical purposes except for telecommunication purposes. Zigbee operates in ISM band mostly 2.4GHz. However, there are some countries like China, Europe and USA use 784 MHz, 868 MHz and 915 MHz respectively. This is done for the long-range communication with lesser data transfer rates. Figure 2.9 shows the image of Zigbee module used with antenna, embedded with platforms and used.

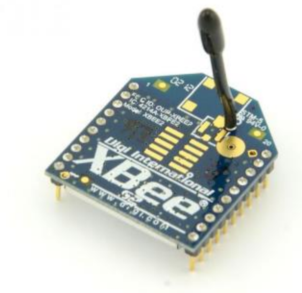


Figure 2.9. ZigBee Module-AB S2-2mw with wire antenna

2.4.4 Radio Frequency or Sub-1 GHz wireless applications

For overcoming the main disadvantage of Zig-Bee, the use of proprietary protocols which restricts its versatility by making several requirements mandatory (Protocols), Sub- Gigahertz technology is an ideal choice. With its applicability in wireless applications requiring long range and low power consumption, narrowband transmissions can transmit data to distant hubs, often 1 km-1.6 km in the space without obstructions and without hopping – 'hop' being a location or a path in between the node which transmits the signal and the node which receives the signal. When it comes to communication between nodes, fewer hops lead to greater efficiency and cost cutting. Sub- 1 Gigahertz communication technology can be used to eliminate most of the hops.

The main advantage of using Sub-Giga Hertz wireless technology is that it offers any application with long-range capability in this frequency band (868 MHz-915MHz), even in obstructed conditions. The cost involved in wireless sensor networks can be reduced since the long-range capability allows a reduction in the number of hops required, granting carrier waves with low frequency the ability of travelling longer distances for a given output power. Governed by the laws of physics, this phenomenon can be demonstrated by using the Friis Formula for path loss.

Apart from the frequency of carrier waves and power given to the transmitter, receiver sensitivity and channel bandwidth also have a significant effect on the range of transmission. A receivers' sensitivity is inversely proportional to channel band width which means waves with narrow band width are sensed efficiently compared to waves with wide band widths. Channel band width is set so that the data rate requirement is met and it suits with the crystal oscillator accuracy. Sub-Giga Hz devices have fully programmable receiver bandwidths ranging from 815MHz to 915 MHz, enabling ultra-narrowband data rates of 100 kbps with -113dBm sensitivity, which is ideal for long-range outdoor sensor applications. On the other hand, Spread spectrum (wide band) signals are not as affected by the interferences from the environment, but the range it can travel is much lower compared to narrow band. One benefit of spreading systems is the ability of using a lower-cost crystal instead of a higher-priced temperature-compensated crystal oscillator (TCXO). Figure 2.10 indicates the difference between narrow band and spread band signals in terms of power distribution.

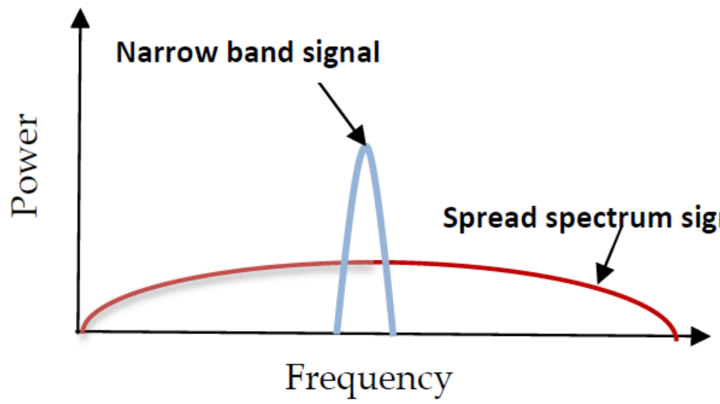


Figure 2.10. Narrowband Vs Spread band

2.4.4.1 Application of Sub-Giga hertz technology in high rise buildings

High rise buildings generally tend to obstruct the carrier waves due to various inherent natures such as thick slabs, metal ducts running through the building and the higher vertical spans. The locations of sensors vary according to the parameters to be monitored. The connection among the sensor nodes and master node/gateway is established using various telecommunication protocols. Wireless sensor networks established using Sub-Giga hertz technology in high-rise buildings overcome issues related to the carrier wave obstruction efficiently compared to the other networks established using other types of protocols. Since

Sub-Giga Hertz technology uses low frequency range which typically varies from 868MHz to 915 MHz it can cover large distances through buildings.

In addition to the protocols discussed under this chapter, telecommunication protocols which are used to establish connection between master node and gateway/ telecommunication tower then internet is discussed in Chapter 3 .

2.4.4.2 Synchronization of sensor nodes using Radio Frequency or Sub-1 GHz technology

When using sensor clusters, synchronizing them to the same timeline to very high accuracy is important in some situations. One such situation is when these sensor nodes are collecting data which will be used collectively and relative to each other. This situation occurs in Structural Health Monitoring projects when the mode shapes need to be plotted using the data collected by sensor clusters. If the sensor nodes were not synchronized to a very high accuracy level, the measured phase angle differs, which decreases the credibility of the result.[18]

Even though several methods are used for synchronization of the sensor nodes, there does not exist a standard method to synchronize the sensor nodes. One such ad-hoc method is given below.

The sensor nodes which need to be synchronized and a calibrated accelerometer which is similar to the accelerometers in the sensor node are placed on a shaker table and are made to experience shocks or vibration which have sudden accelerations within the measurable threshold of the sensors. During this process the readings are obtained to plot acceleration vs time graphs. Such a graph is shown in Figure 2.11 below.

Then the peaks are adjusted with respect to the time axis to coincide the peaks of the sensor nodes to that of the calibrated accelerometer. This methodology ensures synchronization among all the sensor nodes. The synchronization technique using Sub-1 GHz for this system is explained in Chapter 4.

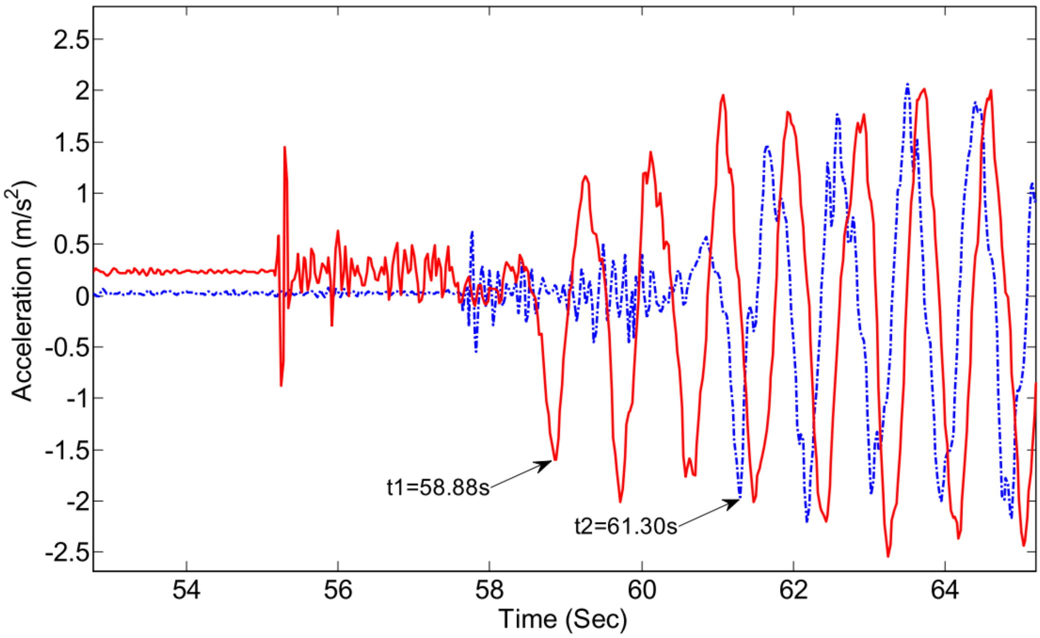


Figure 2.11 Acceleration vs time graph drawn for one of the sensor nodes and a calibrated accelerometer similar to the accelerometer within the sensor node. Source: available in [18].

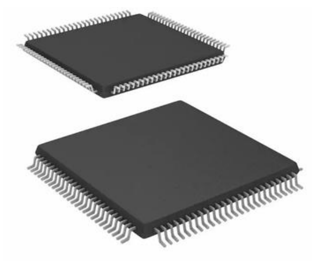
2.4.5 Platforms, Micro controllers and Mini computers

The data collected by sensors has to be saved, Processed and shared with peer sensor nodes. Most of the civil engineering applications require high frequency data acquisition. In order to operate sensors at high frequency and save at the same rate requires good reliable clocks or Real time clocks (RTC). RTCs are responsible for the time stamping thus for the synchronization. The data collection, Time stamping, initial calculations, Synchronization and sending data are the main steps as far as SHM is concerned. These processes take much computational effort thus requiring a reliable robust platform on which the desired functions are scheduled and programmed. Platform is a combination of hardware combined with necessary running environment (i.e Operating systems) in order to run a piece of software. Micro controllers and computers (mini size) are used in Sensor nodes in order to achieve this task. There are several types of Micro controllers available in the industry.

Micro controllers and Micro computers are different in many aspects but it might give a wrong impression that both are same for a person not related to this field. However, Microcontrollers consist of a processor, RAM and other peripherals embedded on a single chip while microprocessor only consists of a processor with a higher capability comparatively. Figure 2.11 shows MSP430 micro controller which is a member of Texas instruments and Figure 2.12 shows an image of microprocessor and a raspberry Pi. Table 2.2 compares microprocessors with micro controllers.

Figure 2.11. MSP430 Launch pad

However mini computers can undertake many instant programs/ tasks on real time basis which require higher processing and cache and ram memories. Computers are



(a)

(b)

Figure 2.12. (a) Microprocessor (b) A minicomputer (Raspberry Pi)

just a collection of I/O s, Storage, Processors/ Microprocessors, ALU (Arithmetic Logic Unit) and a control unit.

Table 2.2. Comparison between Micro controllers and Microcomputers

Microcomputer/Micro processor	**Micro Controller**
Very expensive	Cheaper than Microprocessor
Memory and I/Os are connected externally, thus circuit becomes large	Memory and I/O s are embedded inside
Cannot be compacted as micro controllers	Can easily be compacted in a small space which eases to reduce the size
Power consumption is high	Can be run in batteries
Doesn't have power saving mode	Most of the micro controllers have power saving modes like idle mode/sleeping modes which reduces the power consumption even lesser
Microprocessors are based on von Neumann model/architecture where program and data are stored in same memory module	Micro controllers are based on Harvard architecture where program memory and Data memory are separate.
Mainly used in computers and mini size computers (i.e. Raspberry Pi)	Used for embedded applications like, Auto mobiles, Sensor nodes

2.5 Data loggers and data sinks

In process of any long-term monitoring process, data loggers are the tools which avoids the requirement of person being on site. In building monitoring process and climate monitoring data loggers plays a vital role, due to ample of data these fields have to deal with. Even though the prices of data loggers have decreased compared to earlier days because of the recent advances in electronics, the price of data loggers are still high. The data loggers run on power which requires a reliable power supply. Reliability of power supply of data loggers needs to be higher than other components because the data of entire WSN aggregates at data loggers and the power down even for a small period of time can create data errors [19].

All data loggers share common characteristics except for the fact how the data can be downloaded to the user. Based upon this factor data loggers can be classified into many categories such as standalone USB data loggers, Bluetooth low energy system, Web based data loggers.

USB data loggers communicate with computers or flash drives, using pen drives. However, the USB data loggers becomes expensive with the storage capacity. Similarly, any other type of data loggers become expensive with the storage capacity and other features which are established in data logger in order to make it user friendly. Most of the time data loggers are located in the site itself which makes it hard to correct on failure. Most importantly the data can be collected only under the presence of relevant person[20][21].

Web based data logging system which is discussed in **Chapter 4** deeply, is simply a Server (Computer) which has a permanent I.P address. The features of the Server are partly used for data logging. It is preferred over other data logging due to following reasons

- Generally, servers have enormous data capacity which facilitates data logging for a long period of time.
- Servers are supplied with reliable power supply throughout which increases the credibility of continuous monitoring.
- On webserver, it can be accessed from anywhere in the world and it is possible for increasing the features with high computational capacity (i.e. Data processing and Visualization)
- The data logger can be monitored for its performance online and corrected instantly.
- Data loggers which saves data at higher rates with high accuracy floating points are very expensive, which are replaced by web-based monitoring systems with low cost involved.

2.6 Review of wireless sensor networks in civil engineering context

Any structure that undergoes static and dynamic forces displays complex response which needs to be analysed very carefully. High rise buildings and long span bridges are susceptible for both quasi static deformations as well as dynamic deformations that are higher, due to it is flexibility thus requiring a proper understanding. Both buildings and Bridges undergo loads such as ambient excitations, wind loads, seismic loads, temperature effects and other loads due to movements such as impact loadings and loads due to movements of imposed loads. Simulated or designed behaviour of any structure is thought to be conservative and there is no facility that can predict the loads that a structure would undergo throughout its life span, precisely. In addition to that paucity of data of responses of similar type of building and loads, is used as an excuse for usage of higher design loads that leads to a conservative design which causes enormous wastage of materials. Secondly due to lack of understanding of behaviour of structures after construction, it might sometime create loop holes in design stage which would lead to catastrophic failure. Other than the main reasons mentioned and due to many other reasons, civil engineering structures need to be monitored as keeping them as a living laboratory[22].

Monitoring humans and creating a data base with their health characteristics including weight, has become popular these days. Many researchers especially who monitors demographic variation and health impacts tend to create these databases. However, with the advancement in electronic devices monitoring the movement of people and other weight movements within the structure has become possible with less expenditure. Creating a data base of load which would give a proper idea of load movements in civil structures, thus giving a proper idea of exact loads to be used during design stages. This is however entailed with the requirement of intense monitoring of people by mounting sensors which are almost weightless and easy to implant [23]–[25].

2.6.1 Bridge monitoring using wireless sensor networks

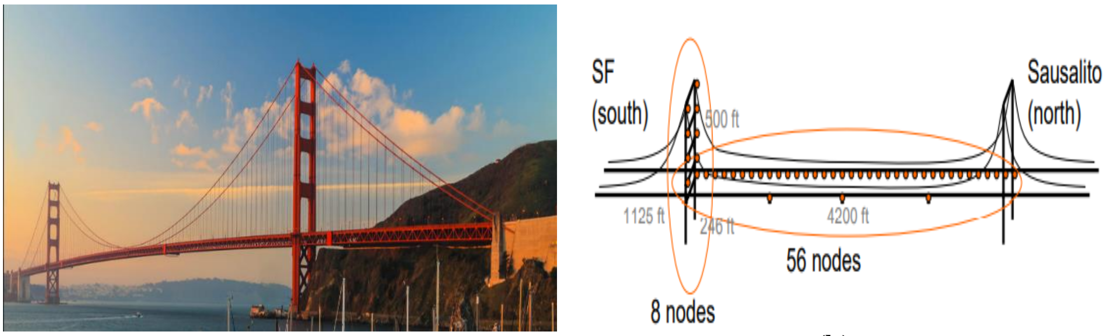
Monitoring of civil engineering structures using wireless sensor networks started with monitoring bridges due to less challenges involved compared to monitoring buildings.

In this research identifying modal characteristics using Operational Modal Analysis (OMA) or ambient modal identification is done. OMA is further discussed in **chapter 6** Operational Monitoring bridges is thought to be easier than monitoring buildings, due to following reasons.

- Ambient vibrations that excite bridge is higher compared to other structures. Which gives higher power spectrum that eases differentiating the modal frequency of the structure.
- Bridge monitoring using WSN is easier due to the open space. Wireless transmission protocols have lesser obstructions that hinders transmission of signals among sensor nodes.
- In buildings services such as iron pipes that are used for fire extinguishing purpose, other aluminium ducts and co axial cables tend to absorb the radio signals that are used for communication among nodes.
- Bridges facilitate line of sight connection which increases the distance between nodes, thus making monitoring possible using lesser number of nodes.

First ever proper bridge monitoring by deploying WSN was done in Golden Gate Bridge (GGB), San Francisco. GGB is 4200ft (1.6 km) long and recognized as a longest and tallest (227m) suspension bridge in the world. The bridge was monitored using **64** nodes distributed throughout the main span and the tower. Ambient vibrations were monitored and collected at 1 kHz which is very high. The sensor network was fully synchronized, and the jitter was achieved to the level of 10µs. The data rate at which data was transferred with 46^{th} hope was 441 B/s. OMA was done and checked with the previous studies and theoretical model of the bridge. The accuracy of sensors was 0.5mg[26].

The main objective of this research was finding the modes that are local. The locations of sensors were selected accordingly. The bridge is hung by cables that connects top flanges of the trusses with main cable every 15.24m. The locations of the sensors were determined after the initial radio test that revealed that after 53 m, the signal strength goes down. So the sensors were mounted at every 150ft (45.5m approximately). In order to cover the entire length 29 nodes were required at one side of the bridge. Figure 2.14 depicts golden gate bridge and the sensor locations respectively.



(a) (b)

Figure 2.14. (a) Golden gate bridge (b) location of sensors throughout the bridge. Source: [25]

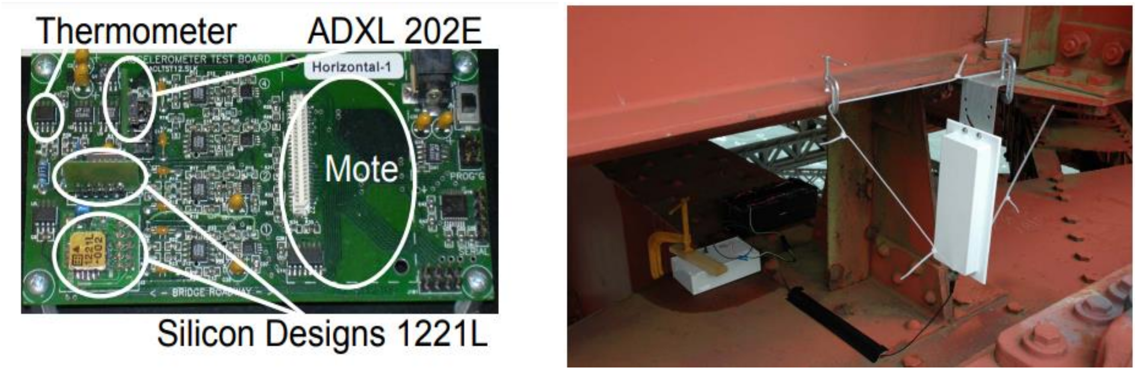


Figure 2.15. (a) Architecture of Sensor node (b) final product of sensor node including radio antennas Source [25].

GGB was monitored using a sensor node that is made up of 2 accelerometers which are very accurate, one is known as ADXL 202E which has a system error of $200\mu G/\sqrt{Hz}$ and other one is Silicon Designs 1221L which has a system error of $32\mu G/\sqrt{Hz}$. AXXL 202E was used to capture -2G to 2G accurately whereas silicon designs 1221L was used to capture -0.1G to 0.1G rage accelerations. The accelerometers were mounted in Mica2 or MicaZ and final product was made. Figure 2.15 shows the sensor node and the final product after the enclosure and addition of radio antennas.

Using the developed system which is inter connected using radio frequency ambient vibration was measured and synchronously. The data was measured at 1 kHz and when it comes to logging average of every sample was saved thus the effective capturing is at **50 Hz.** Each sample set of 20s was plotted as time history then converted in to frequency domain using Fast Fourier Transform (FFT) algorithm. This is also known as computing of power spectral density. The average accelerations are around **5mg** whereas peak acceleration is around **10mg** which correspond to the movement of passing large vehicles.

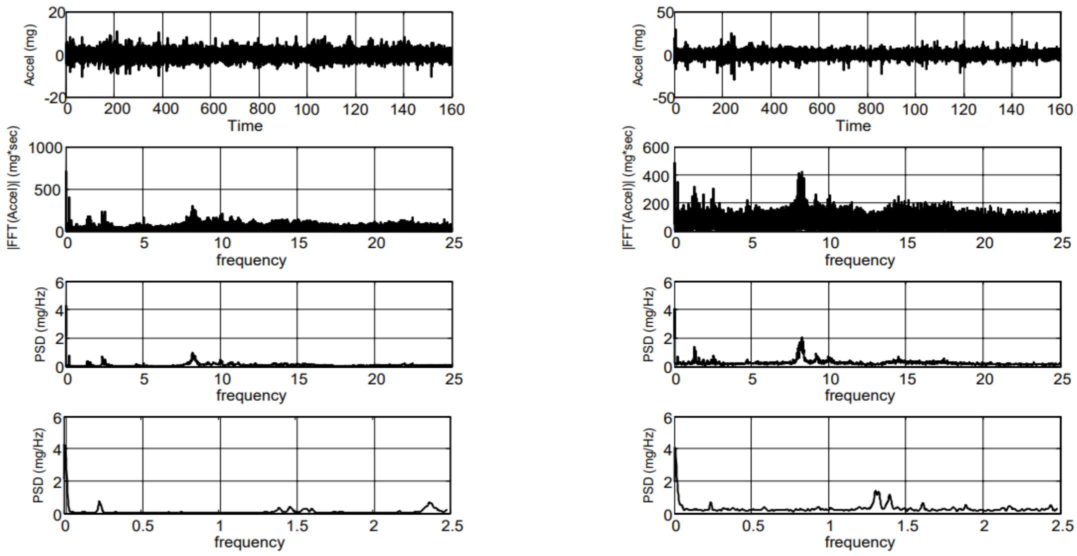
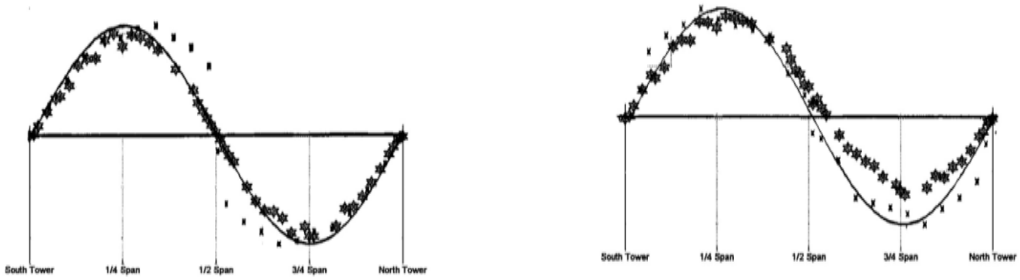


Figure 2.16. Shows the time history plots, FFT of the time history analysis and Power spectral density

A good agreement between model results and the simulated results were observed. As it could be seen in Figure 2.16, the resonance peaks were identified at 0.17 Hz, 0.22 Hz and 0.27Hz which were consistently repeated in all most all the set of data. By identifying the peak (Which is also known as peak picking method) the mode shape amplitude can be plotted. The corresponding phase angle which is also important in order to identify the mode shape of the structure need to be extracted. Using the peak values at the corresponding frequencies and the phase angle the mode shapes can be plotted. Figure 2.17 shows such mode shape plotted using the extracted data.

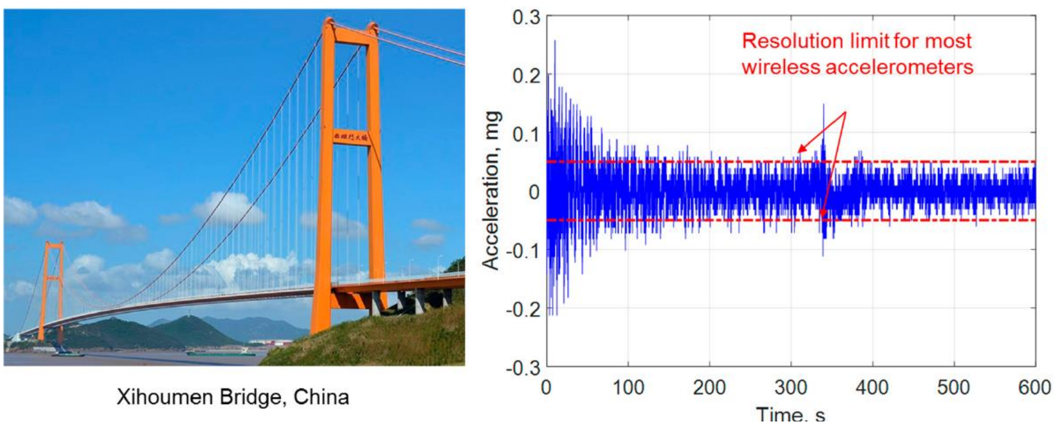


(a) (b)

Figure 2.17. (a) Shows exaggerated vertical mode and (b) shows torsional mode. Source [25]

2.6.2 Application in Xihoumen Bridge

The second largest wireless sensor network is considered to be Xihoumen Bridge which is locates in China. This bridge was monitored using a robust powerful hardware and very reliable software frame work. Since this bridge if considered to be very stiff, the accelerations sensed were very small, High accuracy, Micro electro mechanical systems (MEMS) accelerometers, with low noise were used in order to monitor the accelerations. The accelerations monitored in the bridge, varied in between -0.25 mg to +0.28 mg. Figure 2.18 shows the bridge and typical variation of acceleration observed in the bridge[27].



(a) (b)

Figure 2.18. (a) Xihoumen bridge (b) Acceleration variation of the bridge Source [26]

The bridge selected was monitored using M-A351 accelerometer which has-high resolution (0.06 μg/LSB) with (0.5 $\mu g/\sqrt{Hz}$) noise level. The accelerometer is mounted in a platform industrially known as Xnode which provides a powerful and robust environment. Since the accelerometer works at 3.3V, it is suitable for WSN applications.

The hardware component of this Xnode is the one which contributes for the robust environment. It has three layers of printed circuit boards (PCBs) as shown in figire 18 which has individual functionalities for each layer. Layer one from the bottom is processor board which has LPC4357 processor which can operate with M4/M0 core (ARM Processors) at 204 MHz. The Mini4357 has 32 MB SDRAM which can be used for buffering process. In order to increase the storage capacity MicroSD cards are used. The data transmission part is done by radio/Power board which has Zigbee module (2.4 GHz) in order to establish wireless connection. The 3rd layer which is known as sensor board has 24 Bit Analog to digital converter (ADC) and 5 channels so that 5 accelerometers can be connected at once. All three layers of hardware merged together in order to come up with final integrated product. Xnode can easily be connected with solar power panel and additional sensors and be programmed. Figure 2.19 shows Xnode architecture.

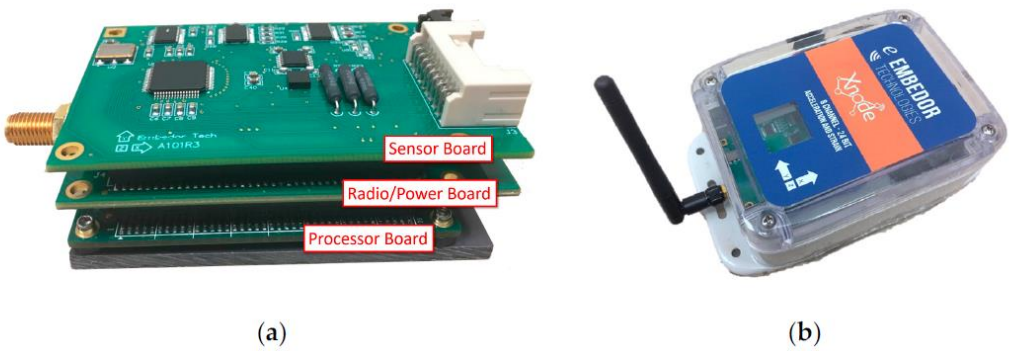


Figure 2.19. XNode Wireless smart sensor (b) Xnode with enclosure

The operating system that is used here is FreeRTOS (Real Time Operating System) along with SOA based middleware. And there is an application (Remote sensing application) running on toolsuite, which facilitates the distributed data acquisition and coordination between gateway and multiple sensors. Several middle wares such as SensingUnit, ReliableComm and GenericComm as depicted in the Figure 2.20 below support remote sensing application.

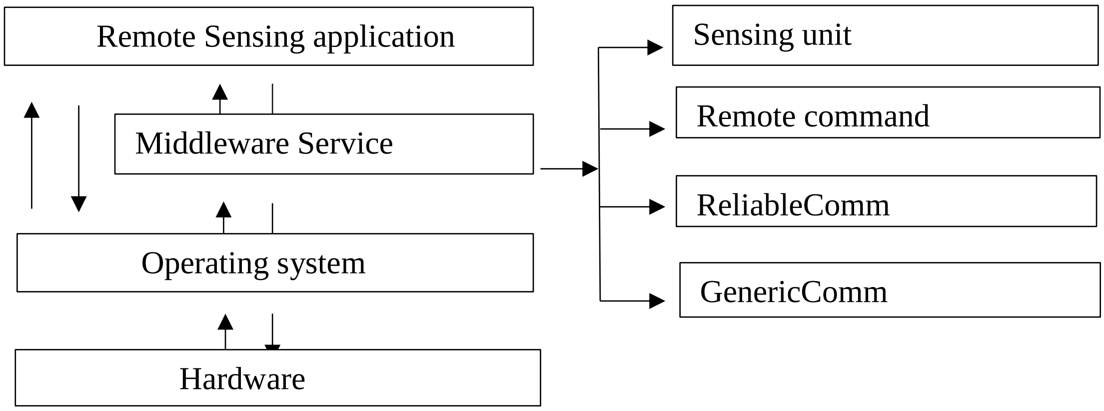


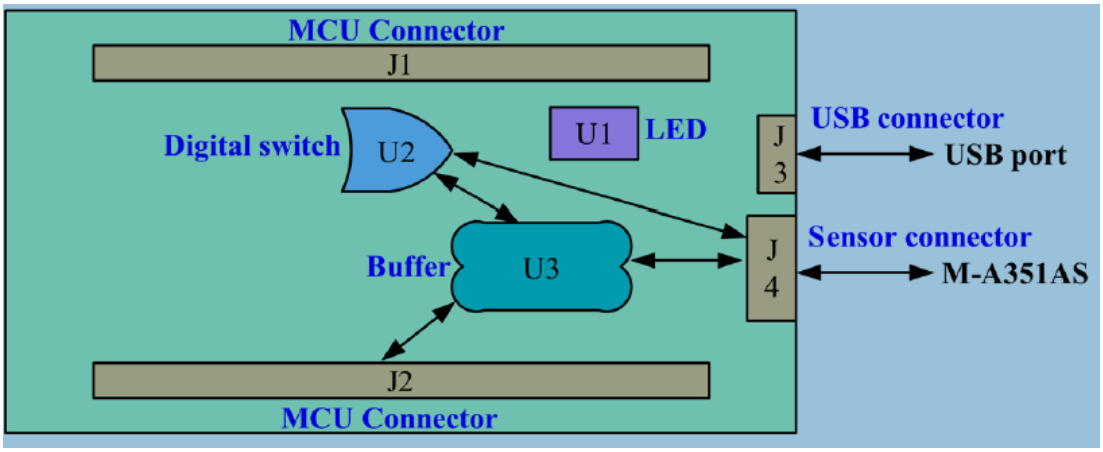
Figure 2.20 Application structure of Remote sensing application: Source [26]

Priority wise the task of sensing and radio task are the top two priorities. Other tasks also come in a particular order which is scheduled by schedulers using FreeRTOS.

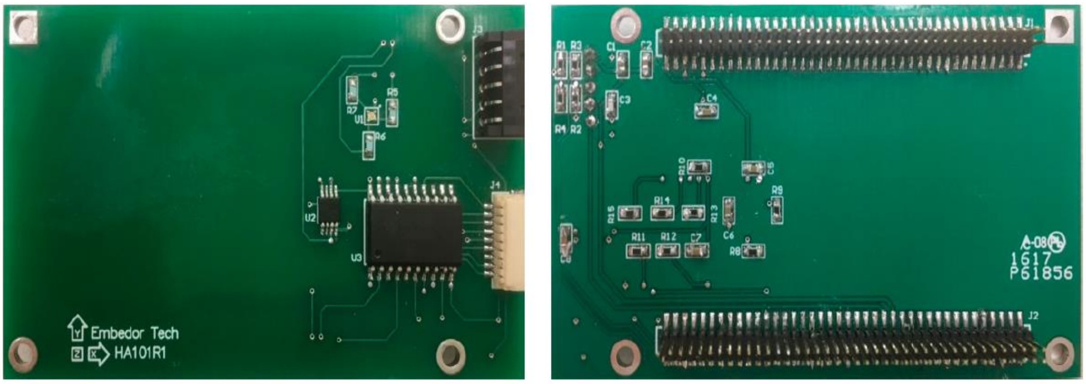
The accelerometers used here is M-A351 shown in figure 20 which is a digital accelerometer with high sensitivity and low noise. The data collected at a rate of 100Hz. The measured resolution is and its noise level is low which 0.06 is µg/LSB and 0.5 µg/$\sqrt{Hz}$. This accelerometer is capable of measuring accurate measurement over large temperature variation. Since the accelerometer is digital there were no additional ADC required.

Figure 2.21. Accelerometer M-A351. Source: [26]

The sensor was connected on the sensor board and the layers of board has already been explained above as shown in Figure 2.21 The concept of sensor board and the real PCB view is depicted in Figure 2.22 below.



(a)



(b)

Figure 2.22. (a) Conceptual diagram of PCB design of Sensor Board Source (b) Real view of PCB design of the sensor board [26].

2.6.3 Monitoring of buildings using wireless sensor networks

Monitoring Building is essentially the same as far as fundamental principles are concerned. However, Monitoring building has inherent challenges compared to bridges or other structures due to following reasons

- In buildings services such as iron pipes that are used for fire extinguishing purpose, other aluminium ducts and co axial cables tend to absorb the radio signals that are used for communication among nodes.

- Building varies in various aspects from one to another. Variation in structural forms, materials, purpose of the building and various loading conditions etc., makes the building monitoring complex. Not only the capturing, the prediction of building behaviour using simulations also becomes complex as the building varies from traditional forms.
- Ambient vibrations that excites the building are small and hard to capture using normal accelerometers with low signal/noise ratio. In following sub chapters two case studies are discussed. One is the Canon tower which is located in china and other one is the building located in Meiji located in Tokyo University.

2.6.4 Applications in canon Tower in Guangzhou, China

This application is considered to be the one of pioneering application of wireless sensor network in buildings. The building is located in Guangzhou in China. The building is 618m height and this is tube in tube structure form. The cross section varies from 50m x 80 m at the bottom to 20.65m x 27.5m at the height of 280m. Then again increases up to 41mx55m.

This building was monitored for various parameters using various sensors such as whether station, Anemometer, wind pressure sensor, zenithal telescope, level sensor tilt meter, accelerometer etc. The system was monitored during construction and service state. During construction this system had 527 sensors and during service state it had 280 sensors thus making this as one of the most complex system. During construction, the 12 number of cross sections were selected whereas during service 5 cross sections were selected. The locations of the cross sections were selected based upon the finite element model where these locations are thought to be experiencing higher stresses. Accelerometers are placed at various locations and complete mode shapes were captured[4]. Figure 2.23 shows the building and the location of the sensors.

Sensor node has 4 channel 16bit analogue to digital converter which has a capacity of collecting data at 100 kHz. The microcontroller used is ATmega128 microcontroller. Microcontroller was the one which is responsible for coordination between various components. Wireless sensing unit is operating at 900MHz Max stream and 2.4 GHz Max stream 24X stream. The long range capability is achieved using 900 MHz whereas higher data transfer rate is achieved using 2.4GHz[26].

Optimum locations were selected by using finite element model and based upon the locations where the higher stresses occurred. However, the locations of the sensors dependent upon following parameters.

(a) (b)

Figure 2.23. (a) image of Canton Tower (b) Image of Sensor locations source:[4].

- **Objective of the sensor placement**: Locations of the sensors varies based upon the parameters we monitor. For example, the locations and the number of accelerometers required would vary based upon the purpose whether it is used for predicting the modal parameters or the local behaviour of the structural element.

- **Sensor node properties**: Sensor node properties such as range of the wireless transmission protocol used would affect the location and the density of the array of the sensors.

- **Cost:** Based upon the accuracy, frequency and data transfer rate required, prize of the sensor node would increase. So, based upon the requirement and the financial limit the number of sensors has a limit thus affecting the density of the array of sensors.

2.6.4.1 Operation Modal Analysis (OMA)

First of all, the response of the building due to ambient vibrations were recorded as time history. There are several system identification techniques available that can predict the desired behaviour by processing the data using various algorithms. In this building the method called peak picking (PP) method is used. PP method is widely used in monitoring of civil engineering structures due to its reliability and the easiness of codifying.

Frequency of acceleration data sampling of the particular building was selected as 50Hz and the time history of data was then converted in to frequency domain using Fast Fourier transform. After converting in to the frequency domain the graphical representation as shown in Figure 2.24 will give a meaningful result. The identified peaks are the point that are relevant for mode shapes where x values represent the relevant frequency and the y value represent the amplitude of the mode shape (Without normalizing). However, the phase angle is the one which determines the starting point of the sinusoidal curve which would be discussed further in chapter6.

Modal damping ratios also can be calculated using peak picking method which is a very useful parameter which designers are interested upon. Table 2.3 shows the extracted frequencies and damping ratios of the Canon tower. And also, it compares the modal assurance criteria (MAC) values which is an efficient tool that is used to check the reliability of the mode shapes predicted.

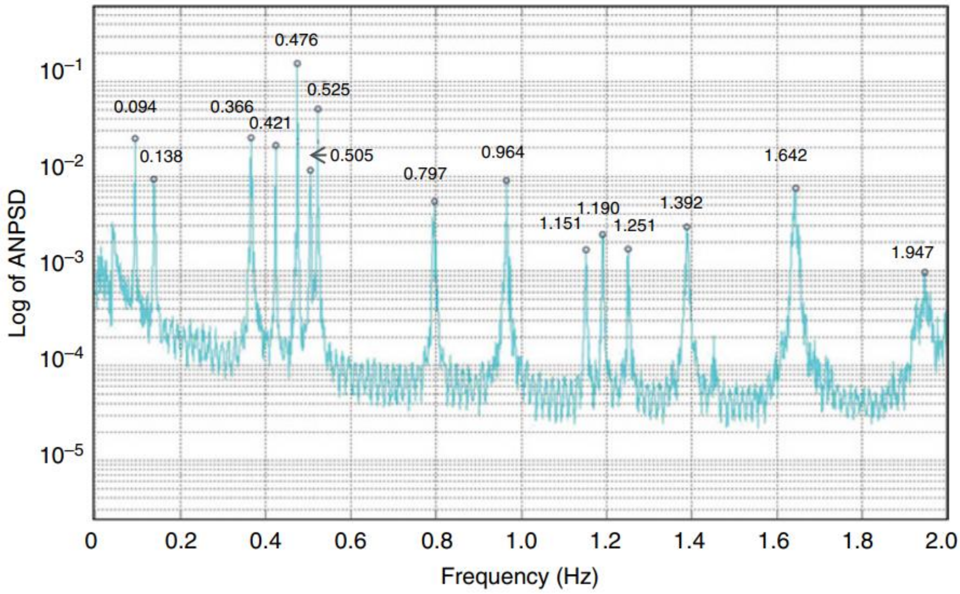


Figure 2.24. Normalized power spectral densities of the acceleration time history. Source [4]

Table 2.3. Modal parameters of canon tower identified

Mode	PP method (Hz)	SSI method (Hz)	FE model (Hz)	Damping (%)	MAC value	Mode description
1	0.094	0.090	0.111	2.97	0.904	Short-axis bending
2	0.138	0.131	0.159	6.18	0.938	Long-axis bending
3	0.366	0.366	0.347	0.24	0.888	Short-axis bending
4	0.421	0.422	0.369	—	0.888	Long-axis bending
5	0.476	0.474	0.400	0.07	0.869	Short-axis bending
6	0.505	0.504	0.462	0.38	0.104	Torsion
7	0.525	0.520	0.487	0.07	0.783	Long and short-axis bending
8	0.797	0.796	0.738	0.20	0.797	Short-axis bending
9	0.964	0.966	0.904	0.33	0.771	Long-axis bending
10	1.151	1.151	0.997	0.10	0.701	Short-axis bending
11	1.190	1.191	1.037	0.03	0.753	Long-axis bending
12	1.251	1.251	1.121	0.16	0.161	Torsion
13	1.392	1.390	1.245	0.35	0.793	Coupled bending and torsion
14	1.642	1.643	1.504	0.25	0.623	Coupled bending and torsion
15	1.947	1.946	1.726	0.59	0.609	Coupled bending and torsion

Using the values of the peak and the phase angle, mode shapes can be plotted and compared with the mode shapes of the simulated model. Figure 2.25 shows translational and rotational mode shapes of Canon tower.

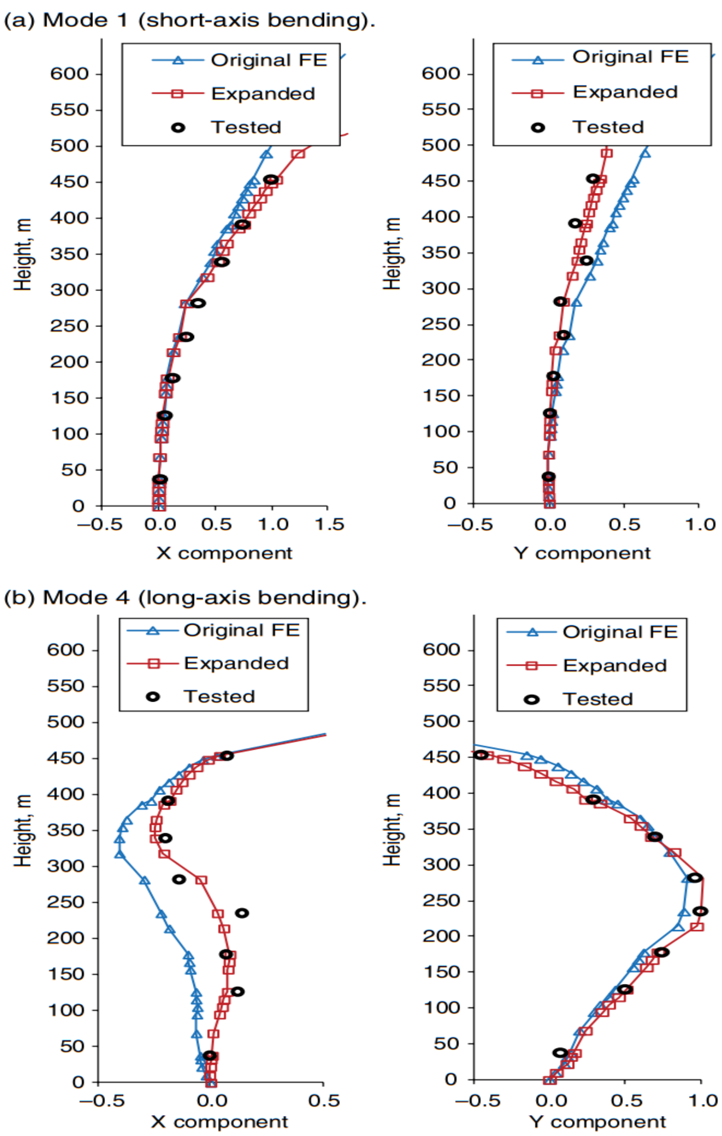


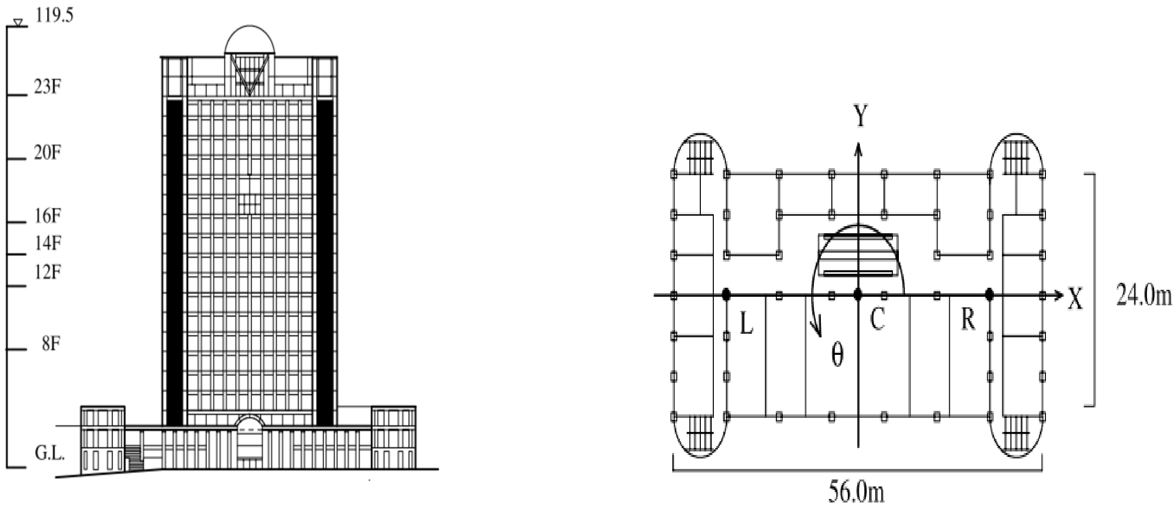
Figure 2.25. First and fourth bending Mode shapes compared with the mode shapes produced by Finite element model

The method of extraction of modal damping ratios and the exact way of Fourier transform application are discussed in chapter 6 along with a two case studies.

Another case study which describes exact way of extraditing modal damping ratios and mode shape for building is, Monitoring of Meiji University which is 120m high.

This building was monitored 60 months continuously and variation of natural frequencies from first mode to 4th mode was monitored throughout the period.

This building consists of 23 floors and the accelerometer data was collected at 50 Hz. The low pass filter used is 10Hz because all the natural frequencies (i.e. higher modal mass participation ratio) are included within 10 Hz [28]. The measurement data was only 30 minutes of data. Figure 2.26 shows the locations of the sensors in the elevation and plan view.



(a) (b)

Figure 2.26. (a) Senor locations in the Elevation of the building (b) Locations of the sensors in plan view (L, C, R)

The natural frequency is identified using peak picking method and the location of particular frequency is identified such that the peak of a particular frequency is nearly equal to the average of the 5 peak amplitudes in the neighbourhood.

The damping ratio is calculated well known $1/\sqrt{2}$ method where the value in vertical axis is located by multiplying the peak value by $1/\sqrt{2}$. n th damping ratio is calculated by the equation

$$\varsigma_n = \frac{1}{2} \times \frac{\delta f}{fn} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.2)$$

Where the ς_n is the damping ratio corresponding to n[th] mode. δf is the band width in frequency domain. fn on the frequency transform. Figure 2.27 shows the identification of peak of the spectrum and the calculation of modal damping ratios.

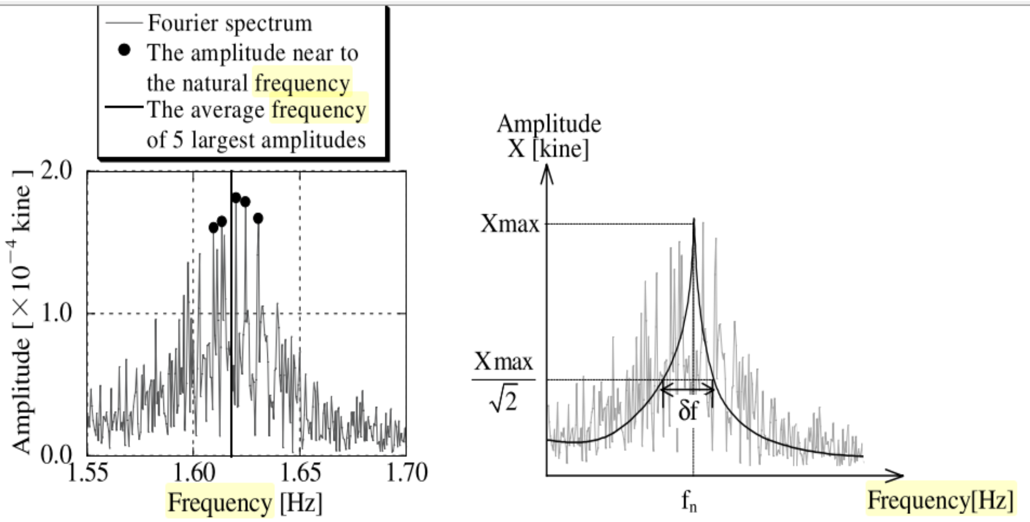


Figure 2.27. Identifying the peak (Left) and Evaluation method of modal damping ratio using $1/\sqrt{2}$ method(right)

Using the above method described above, natural frequencies and modal damping ratios are calculated and tabulated as shown in Table 2.4 below.

Table 2.4 Natural frequencies and modal damp ratios of the building considered

Mode Number	Natural frequencies (Hz)	Modal damping ratios (%)
1st Mode	0.51	0.66 %
2nd Mode	1.62	1.03 %
3rd Mode	2.76	1.2 %
4th Mode	4.08	1.70 %

CHAPTER III

3.0 DESIGNING OF THE WIRELESS SENSOR NETWORK

Even though, the whole research lies on interpreting the data to analyse the modal shapes and identify the defects or discrepancies in the structure, designing the wireless sensor network plays a major role than the data interpretation section. The reason for this imbalance is that, to make correct predictions nevertheless accurate ones, the data collected should be correct and accurate to the needed degree in the first place. Therefore, we need to design a wireless sensor network system which will facilitate our system with the needed amount of accuracy and correctness.

3.1 Methodology

The methodology followed in order to achieve the objectives, is described below

- To do a broad literature review and study the existing wireless sensor networks used for monitoring civil engineering structures and get a thorough knowledge in the methodology to be used to extract modal characteristics of real building using acceleration data collected.
- Checking various accelerometers that are used in industry, for its robustness and accuracy for using this purpose. Calibration methods and noise level was checked in order to make sure accurate response of the building was captured.
- Developing a node/ sensor node which is capable of collecting data at high rate from accelerometer and save. The node consists of mini sized computer and a micro controller which is capable of establishing network with peer nodes using sub-1 GHz wireless technology protocol.
- To select a target building which is tall enough to produce perceivable acceleration and make a mathematical model of the building using commercially available finite element packages.
- Identifying the locations of sensors using mathematical modal made, and mounting the sensor nodes at identified locations of the building.

- Collecting the data for appropriate period of time, processing the data in order to extract modal parameters and visualize the response of the building online.
- Compare the results predicted using mathematical models with the results obtained by processing the data obtained by mounting sensors in the target building, and arriving at conclusions.

3.2 Methodology of management of the data until the gateway of the network

Every network that exists for a specific purpose, has three main functionalities throughout the network. Every node of the network concentrates only on these three functionalities. These functionalities are receiving the data, processing the data and transmitting the data. Generally, every node of a network, does not have any idea how the data is processed by any other node or how is it transmitted from that specific node.

3.2.1 Processing of data by the components of our system

To understand the design that is implemented in this system, we should have a clear understanding about the components of the Wireless Sensor Network (WSN), which is explained in Chapter 2.3, which will then be correlated with the Hardware components that we are using in this system.

The common components of a wireless sensor network, as explained in Chapter 2.4 are, a trivial sensor node, a master node and a gateway. In our system, the trivial sensor nodes are the nodes which collect the data but which are not connected to the gateway, the master node is the node connected to the gateway and the gateway is the router which transmits the data packets to the internet.

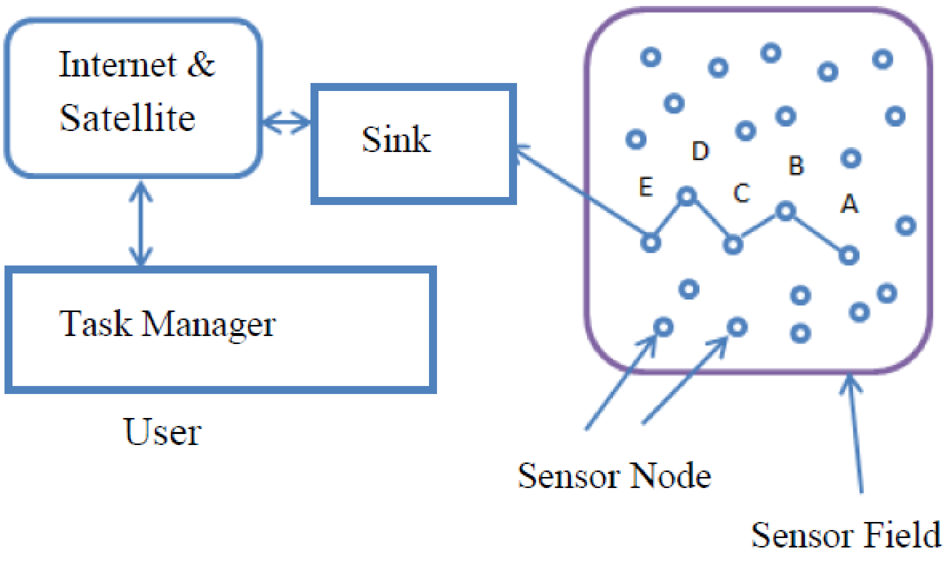
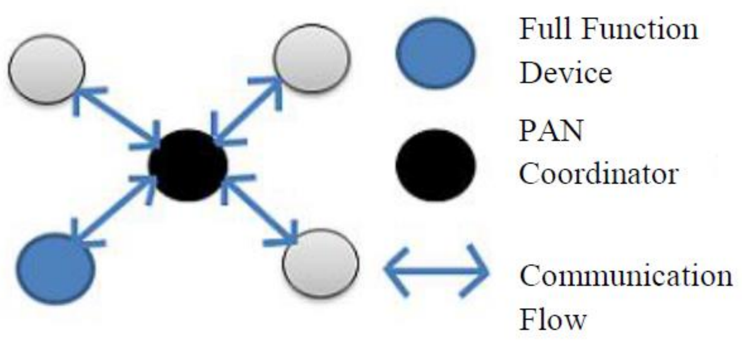


Figure 3.1 Wireless sensor network representation Source: available at [1]

The wireless network is designed as shown in Figure 3.1. The internal workings of the sensor network can be in various configurations. These configurations are known as various topologies of the network. Generally, these configurations would have an administrator node to provide instructions to the whole network which is known as the Personal Area Network administrator. (PAN)



(a)

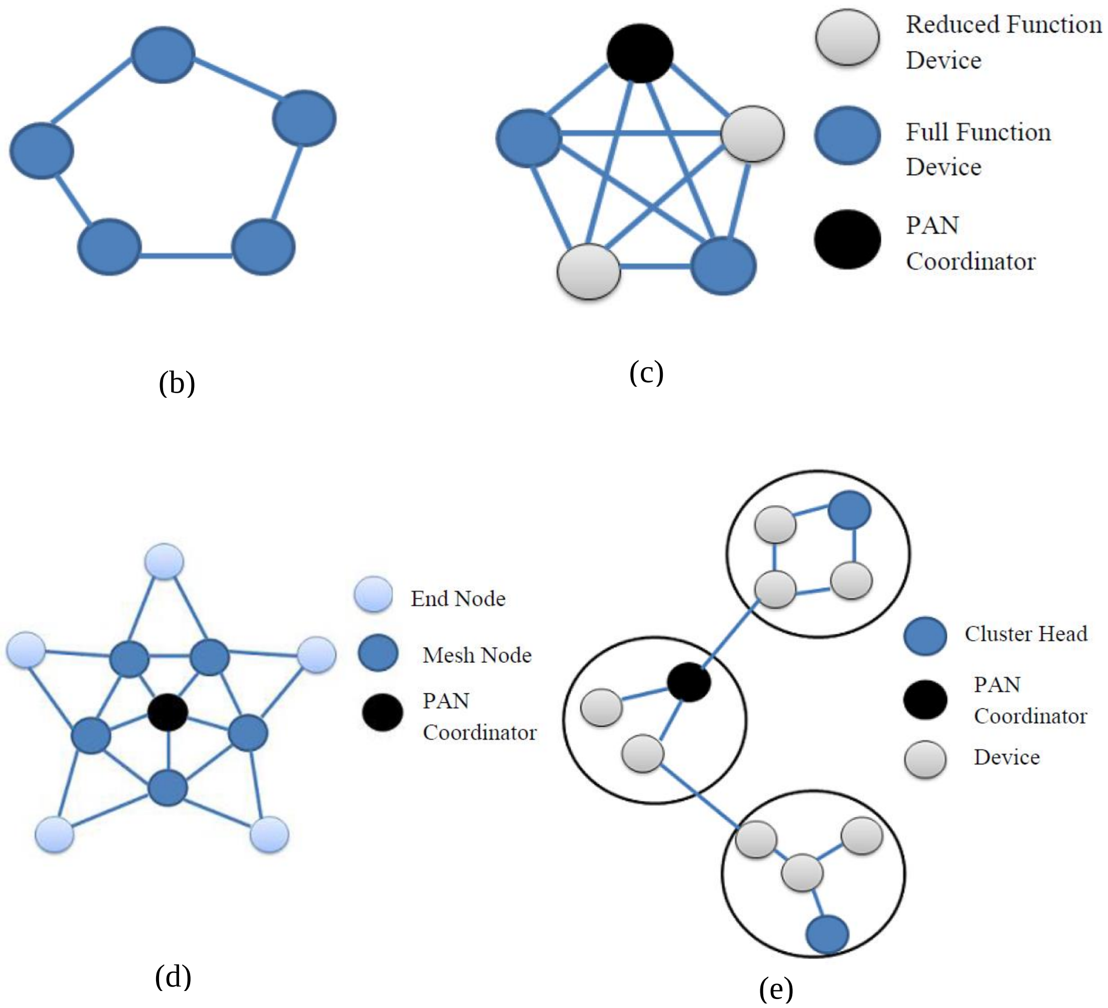


Figure 3.2. (a)Star wireless topology representation (b)Ring wireless topology representation (c)Mesh wireless topology representation (d)Star-mesh wireless topology representation (e)Cluster tree wireless topology representation Source: available at [1]

Figure 3.2 illustrates how the nodes are positioned inside the sensor network. Our system has a cluster tree wireless sensor network topology to ensure various functionalities. The crucial factor to choose this specific topology is the synchronization of nodes. A brief introduction of various wireless topologies is given below.

1) Star topology: Here the master node and the PAN coordinator will be the same node and the only communication possible will be between the typical nodes and the central master node.

2) Ring topology: When the sensor nodes use message passing as the only mode of communication between themselves, a ring topology is preferred. If one node becomes obsolete the whole system ceases to communicate.

3) Mesh topology: When the sensor nodes send the same data to multiple receivers with the assurance that somehow the data will reach the desired destination, mesh topology is used.

4) Star-Mesh topology: Star mesh topology is a hybrid version of the star topology and the mesh topology.

5) Cluster tree topology: Cluster tree topology appears when every node is fully functional and the clusters of sensor nodes are interconnected and managed by one PAN master node. This is the configuration of our system[29].

Our system can also be redefined into being a star-mesh network topology with some modifications to the system. This is made possible to reduce the jitters (Synchronization error). We chose to establish this system with cluster tree topology as our network configuration to increase the range that our system can cover.[30] Using the cluster tree topology configuration, multi hopping system is implemented where when a node wishes to communicate with the node out of its range, the data packets are sent to a node which is accessible by itself and which is in close proximity to the next node in the route which leads to the desired destination[31][32].

These components are made up of several hardware components, which should be discussed to understand the functionalities of the components mentioned above.

3.2.1.1 MMA8451 Accelerometer

Accelerometers belong to a sensor class which are known as inertial measurement units. This class of sensors measure the movement of inertial bodies. The specialty in this class of sensors is that the motion measured is relative to that of the earth[33].

The sampling frequency that was used in this accelerometer is 100Hz[34]. The reason to choose this sampling frequency is explained in Chapter6.

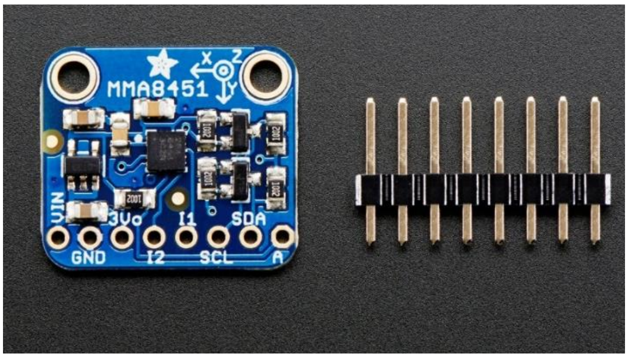


Figure 3.3. Adafruit 14-bit 3 axis accelerometer MMA8451 Source: Adafruit learning official website

There are several types of accelerometers available, but the use of Micro Electro Mechanical Systems (MEMS) accelerometers in the digital domain is much preferred[33][35]. MEMS are mechanical arrangement of electrical components which measure the variations due to the change in their mechanical arrangements.

There are 3 basic types of MEMS accelerometers.

1) Piezo electric MEMS accelerometers: Accelerometers which use piezoelectricity to measure acceleration are piezo electric mems accelerometers as shown in Figure 3.4.

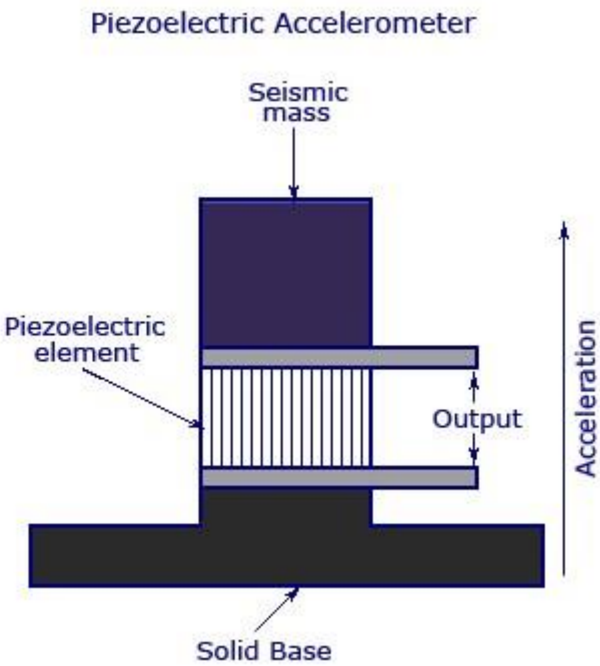


Figure 3.4. Structure of a piezoelectric accelerometer. Source: Instrumentation Today official website.

Due to the force acting upon the seismic mass, the piezo electic element will be compressed and the piezo electricity will be measured which can then be correlated to the acceleration of the whole system.

2) Piezo resistive MEMS accelerometers

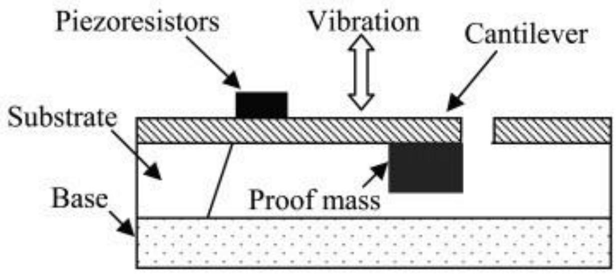


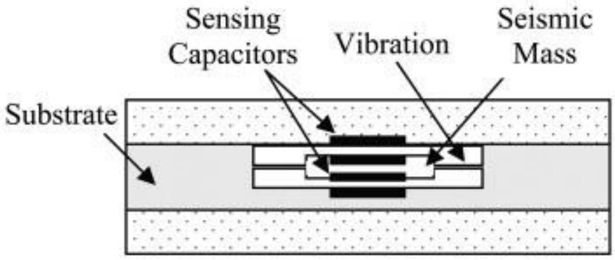
Figure 3.5. Piezo resistive accelerometer. Source: Available at [6]

Due to the vibration on the cantilever beam, the acceleration is computed. Figure 3.5 represents how a piezo resistive accelerometer is formed.

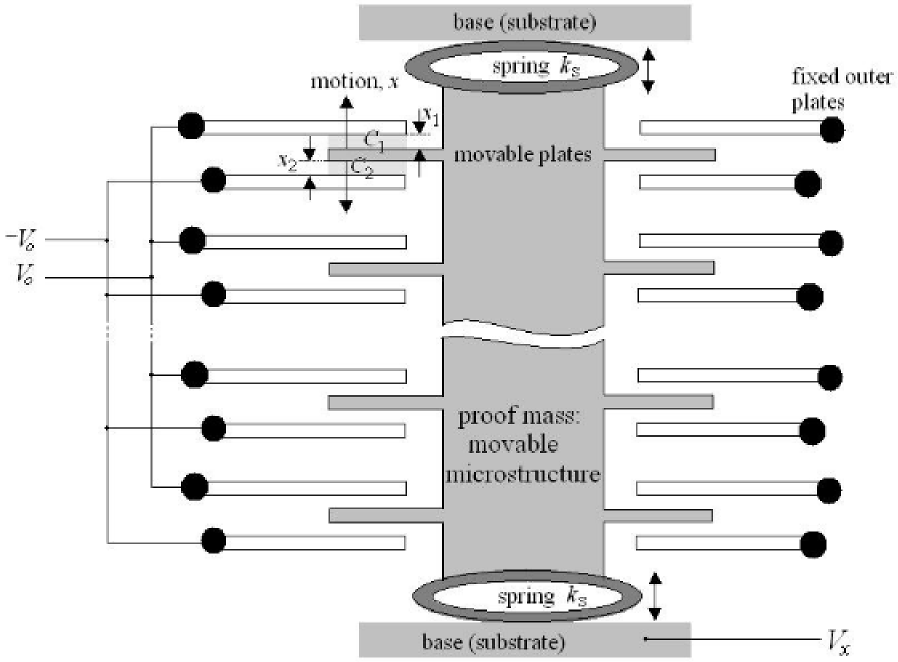
3) Capacitive MEMS accelerometers

Capacitive accelerometers use the capacity between two small membranes which will be arranged in such a way that a small acceleration will move one of the membranes in relation to the other. Then the capacitance between two membranes are calculated with the use of the voltage change between the consecutive membranes which will then be used to calculate the acceleration of the system. Figure 3.6 shows how the capacitive based accelerometer is structured and figure 3.7 shows the block diagram of MMA accelerometer.

MMA8451 is an accelerometer which is a capacitive MEMS based accelerometer which uses I2C based communication (Explained in 3.1.2) to send data to the requesting device.



(a)



(b)

Figure 3.6. (a)Capacitive MEMS based accelerometer (b)Detailed view of a capacitive MEMS based accelerometer. Source: Available at [6]

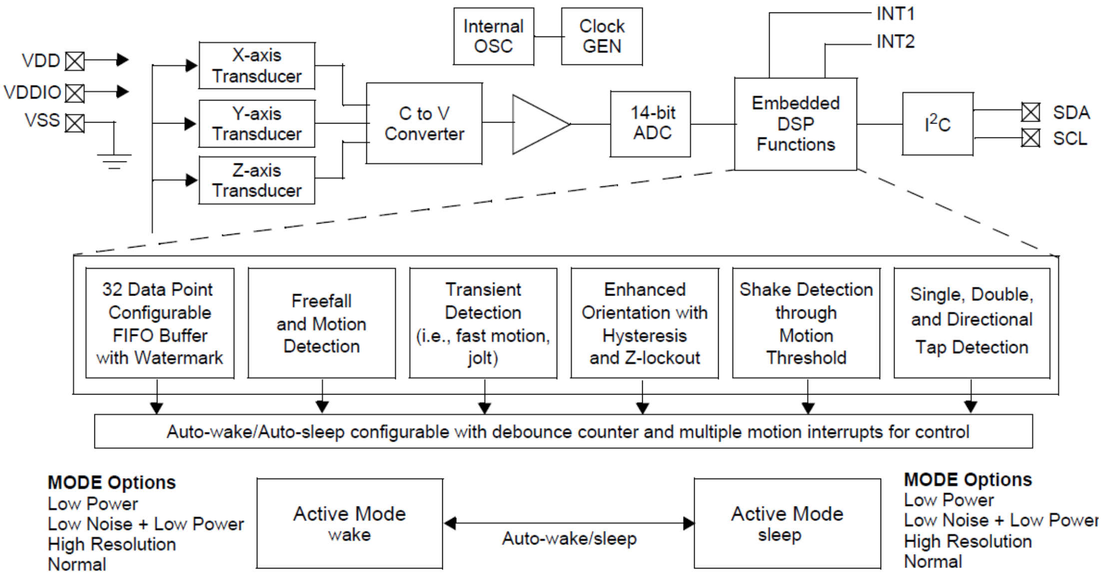


Figure 3.7. Block diagram of MMA8451. Source: Available at Adafruit official website

Table 3.1. Specifications of MMA8451. Source: Available at Adafruit official website

Specification	**Value**
Supply Voltage	1.95 V to 3.6 V
Supply Current	6 µA to 165 µA
Operating temperature range	-40 to + 85
Output data rates	1.56 Hz to 800 Hz
Frequency based nodes	99 µG/Hz
Output (Number of data bits)	14 bits or 8 bits
Interface type	I^2C
Sensitivity at 2g mode	4096 counts/g
Sensitivity change vs. Temperature	0.008 % / ºC

3.2.1.2 CC1310 development board

Figure 3.8. Texas instruments CC1310 Development board Source: Texas instruments official website

This development board is a platform which facilitates high quality standard development which is also low in cost and power efficient. This is the main reason that helps CC1310 development board to be used in wireless sensor network nodes. This device also has transmitters and receivers which support RF telecommunication. Figure 4.5 shows the block diagram of how the RF core and processing core are separated while collaboratively working together. The software which runs on top of the physical layer TI-RTOS which supports all the operations performed on this device.

CC1310 Ultra-Low-Power wireless MCU which transmits data in Sub-1 GHz consists of a powerful Arm Cortex M3 processor with 48MHz clock speed. This development board consists of 32KB, 64KB and 128KB of programmable flash, 8KB of SRAM for cache which can also be used as general-purpose RAM and a RF core which deals with Radio transmission. This class of microcontrollers are developed to support a single core SDK and a variety of development environments. This 16-bit architecture development board also has various peripherals which can be linked to the GPIO pins and supports various inter IC communication standards such as I^2C, I^2S, SPI and UART. This set of microcontrollers are RoHS (Restriction of Hazardous Substance directive) compliant. These set of characteristics facilitate CC1310 to be a suitable microcontroller to be used in our system. These characteristics are arranged in a suitable functional method which is represented by Figure 3.9.

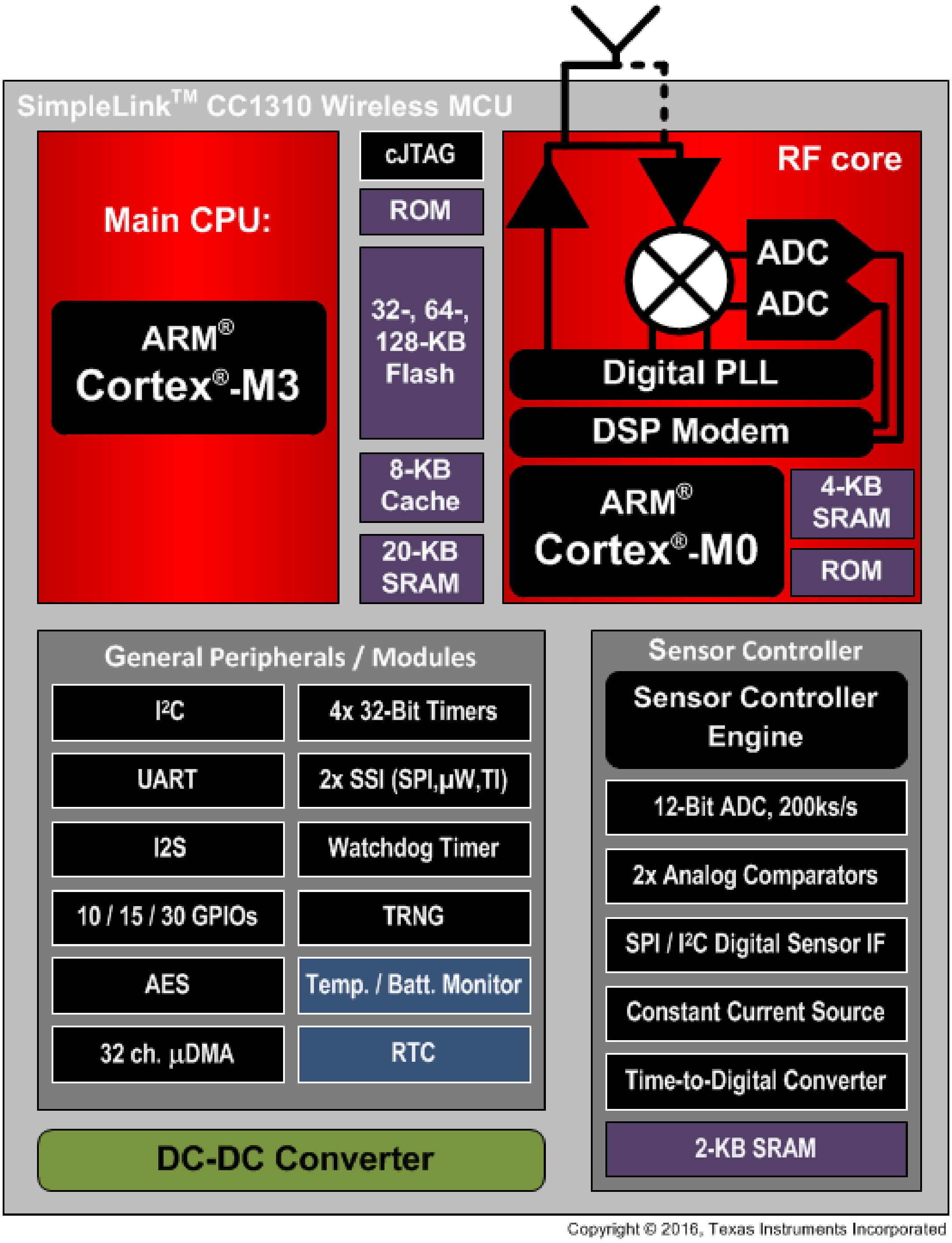


Figure 3.9. Functional block diagram of CC1310 Source: Available at [9]

3.2.1.3 CC3320 development board

The purpose of this development board is to get the torsion of the buildings using the acceleration of two nodes. Figure 3.10 shows how the torsion could be measured using accelerations of two points in space.

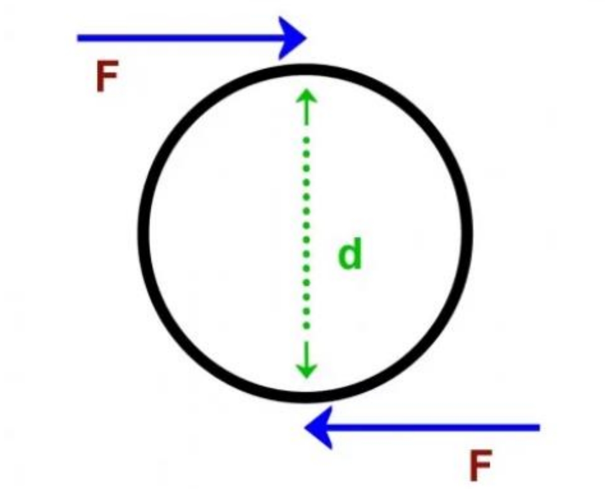


Figure 3.10. Concept of Torsion two acceleration components

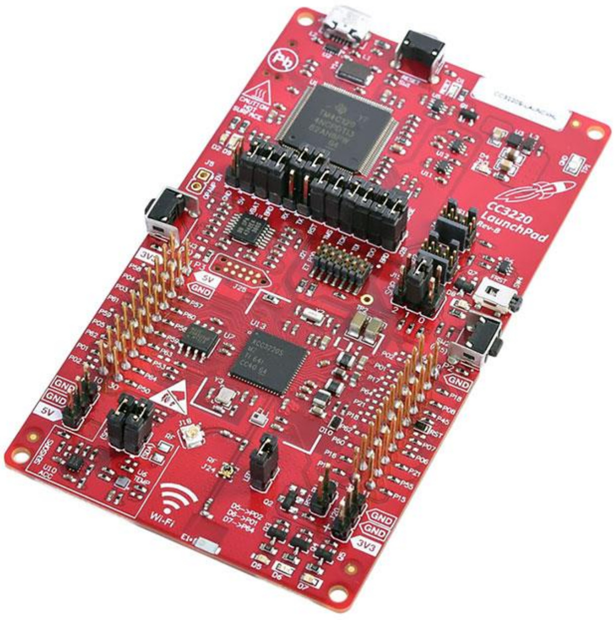


Figure 3.11. Texas Instruments CC3220SF development board Source: Texas Instruments official website

CC3220SF development board is almost similar in processing to CC1310 but supports Wi-Fi transmission instead of Sub-1GHz RF transmission.

CC3220 wireless MCU which transmits data with the help of Wi-Fi protocol consists of Arm Cortex M4 processor with 80MHz clock speed, 256KB of RAM and 1MB of executable flash. This class of microcontrollers are developed to support a single core SDK and a variety of development environments. This development board also has various peripherals which can be linked to the GPIO pins and supports various inter I^2C communication standards such as I^2C, SPI and UART. This set of microcontrollers are RoHS (Restriction of Hazardous Substance directive) compliant. The detailed description of CC3320 is shown in Figure 3.12 and Figure 3.13.

This device also has an accelerometer and a temperature sensor embedded in it which is calibrated to high precision. To calibrate the error due to the temperature change, this temperature sensors can be used to send temperature readings at specific intervals to accommodate into the data and to manage specific errors.

Temperature sensor : tmp006

Accelerometer : bma222

Table 3.2. Specifications of bma222

Specification	Value
Supply Voltage	1.2 V to 3.6 V
Supply Current	139 µA
Operating temperature range	-40 to + 85
Output data rates	8 Hz to 1000 Hz
Frequency based nodes	1 mG/Hz
Output (Number of data bids)	14 bits or 8 bits
Interface type	I^2C
Sensitivity at 2g mode	4096 counts/g
Sensitivity change vs. Temperature	0.02 % / ºC

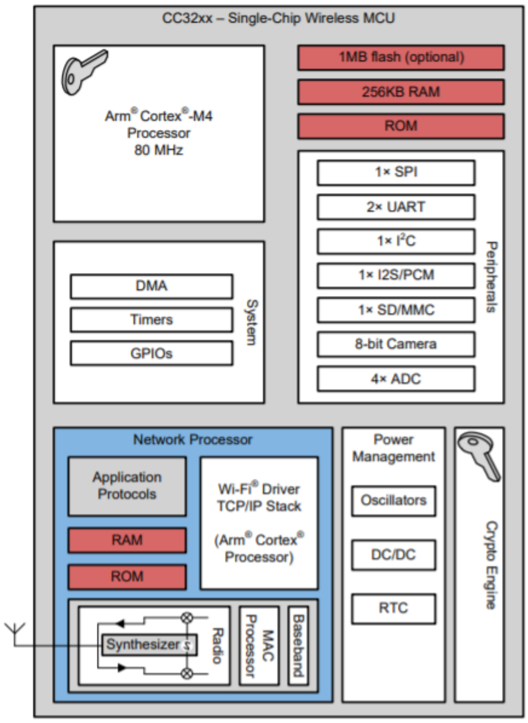


Figure 3.12. Hardware overview of CC3220SF Source: Texas Instruments official website

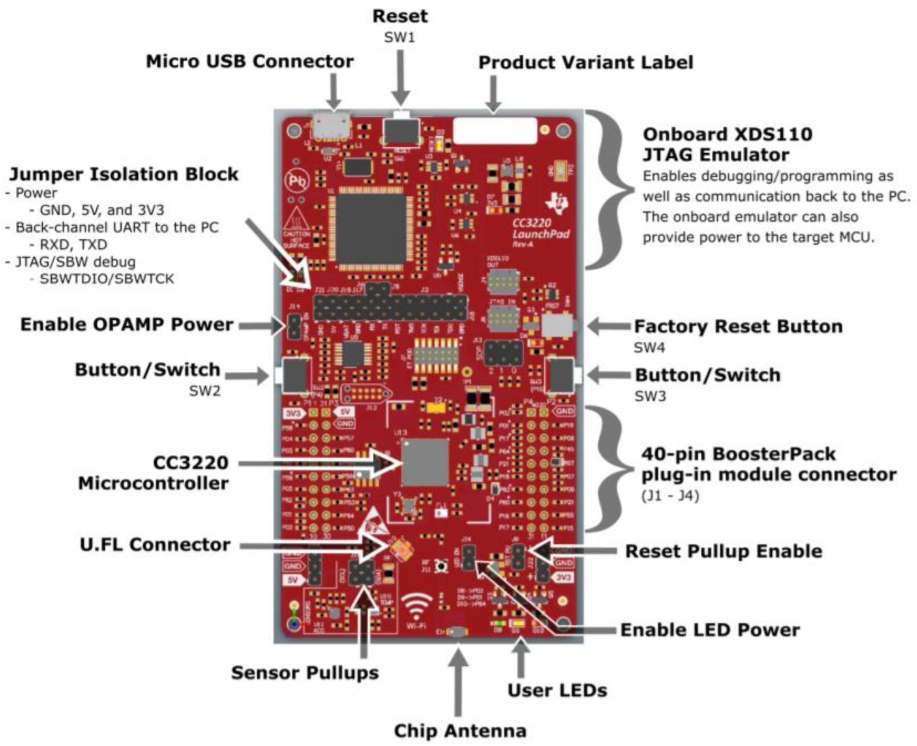


Figure 3.13. Pin layout of CC3220SF Development board Source: Available at [10]

3.2.1.5 Raspberry Pi 3B+

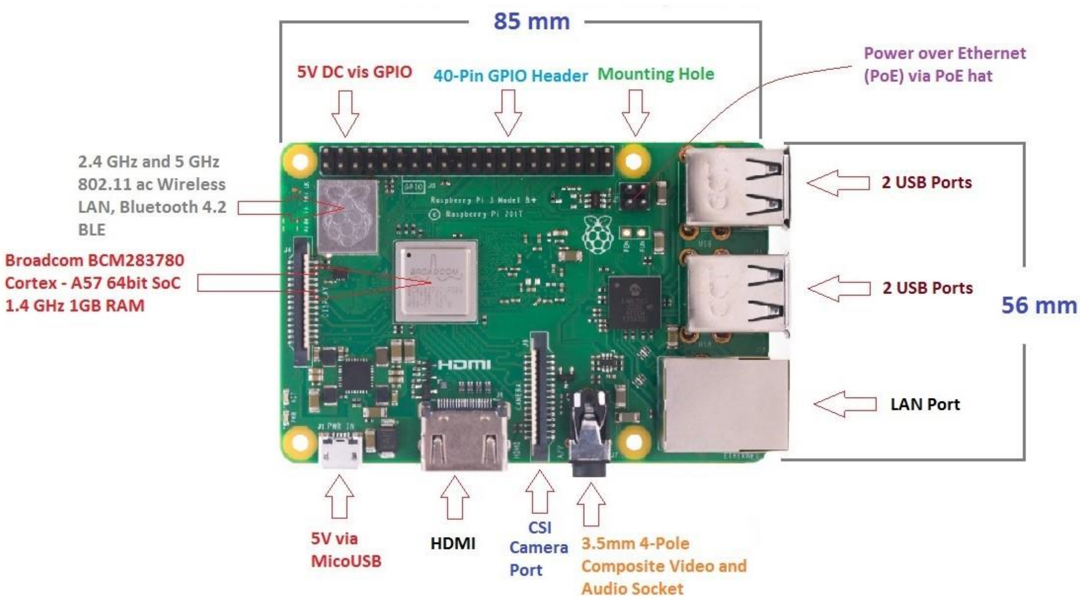


Figure 3.14. Pin layout of Raspberry Pi 3B+

Raspberry pi which is a mini-sized computer who acts as the main brain of a node, is the processing board which controls all the actions of the node. We can reprogram this device to manage all the changes in the system. In our system, Raspbian OS was installed on top of the physical layer which will be used as the mediator of all our system applications which runs on Raspberry pi.

3.2.1.6 Router

Router acts as a gateway between our network and internet. Purpose of having a router and how it functions is explained in the Chapter 5. Router receives the data packets transmitted by Raspberry Pi to the router using Wi-Fi data-link communication protocol.[36]

To summarize the purposes of all the hardware components in the wireless sensor network, Raspberry pi receives data from the accelerometer and sends it to Texas instrument boards which can send the data packets through Multi Hop method by using the RF core which will then be transmitted to the router. The router finally uses GSM telecommunication standard to transmit the data to the server.

3.2.2 Transmission of data between the nodes

Even if a node knows how to collect the data or process the data that is present within its memory, the node should understand how to receive and transmit the data in a suitable format and in a suitable methodology so that the next node can receive the processed data. If this is not achieved the whole purpose of having a network is lost.

As nodes are made up of semiconductor chips, the transmission between hardware components connected by a wire is dealt with communication protocols.[37] In our system as the hardware components such as MMA8451 deals with serial transmission of data, a description of all the serial communication protocols is given below to understand how the hardware components in our system as well as other systems communicate with each other[38].

The serial communication protocols that are present and widely popular are I^2C, SPI and UART communication protocols. These protocols deal with sending and receiving data between wired hardware components in a systematic manner such that the devices know who is communicating with whom, the data that is associated with the transmission and the command that is associated with the communication[39].

1) I^2C serial communication protocol: Inter Integrated Circuit deals with multi master and multi slave communication in a half-duplex manner. The details of the communication are shown below through Figure 4.15.

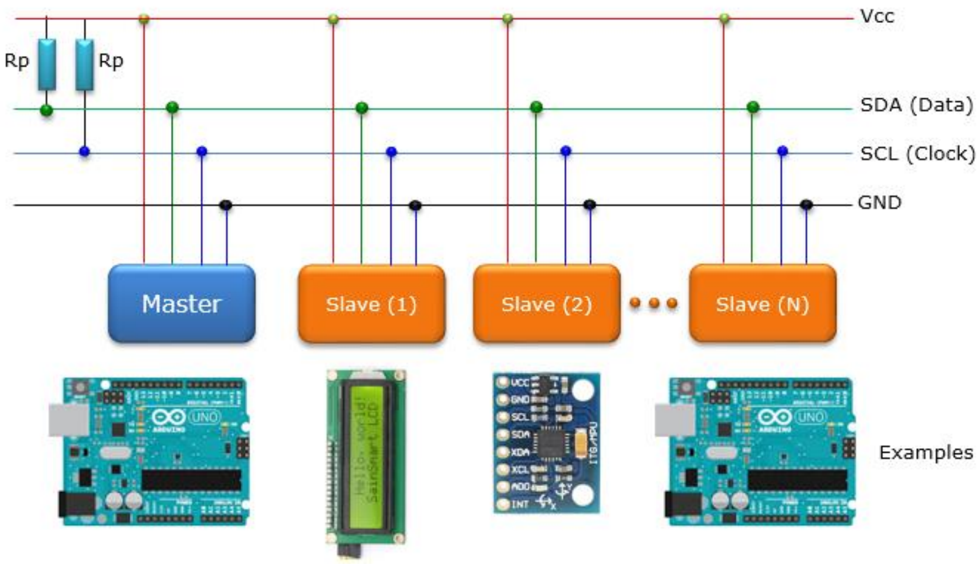


Figure 3.15. Connections between the components in an I2C communication system. Source: ShareTechNote official website

Figure 3.15 represents the connections between hardware components in an I2C based communication. Every device that communicates with this protocol deals with 4 wired connections. Two of them are for power and the other two are for the communication between the components. The communication lines Serial Data line (SDA) and Serial Clock line (SCL) deal with the data transmission in an efficient manner. The SCL line deals with the clock pulses and the SDA line deals with the data bits that are sent through the wire. Figure 3.16 represents how these lines interpret the signals sent through them.

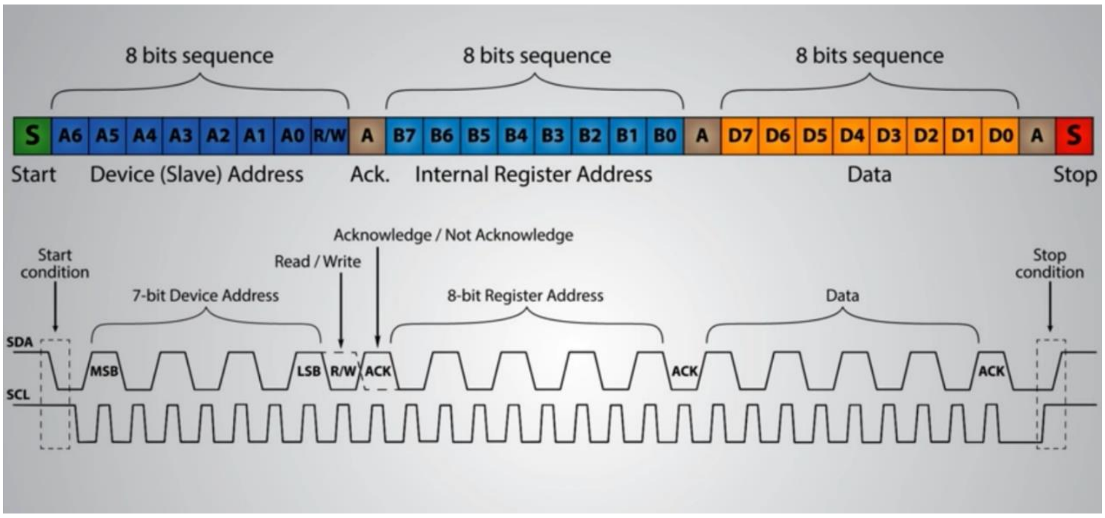


Figure 3.16. Signal interpretation by the SDA and SCL lines in I2C protocol. Source: HowtoMechatronics official website

Both SDA and SCL lines are pulled up by pullup resistors which will make sure that both lines are in the HIGH voltage level in the general scenario when there is no communication occurring in the bus. The SDA line sends a start bit which is a logic ZERO which will then be followed by continuous clock pulses on the SCL line. Then the transmission occurs through SDA line. The first 8 bits of the incoming data after the start bit represents the address of the connected device that needs to be communicated with, followed by an read or write bit, an acknowledgement bit, 8 bits representing the internal register address, another acknowledgement bit,8 bits of data, final acknowledgement bit and then a stop bit which will be a logic level HIGH bit. This is the structure of a data packet through an I2C communication bus which will be interpreted as mentioned above. Figure 3.17 shows a real-world example simulation of how and I2C bus communicates.

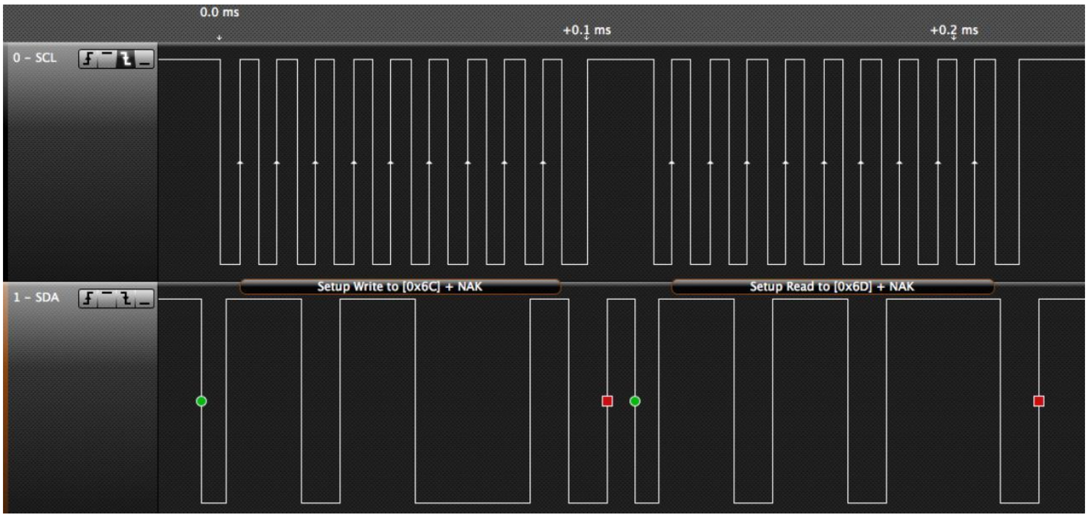


Figure 3.17. A captured packet in an I2C protocol-based communication. Source: MikroElectronika official website

2) SPI serial communication: Serial Peripheral Interface is another communication protocol adapted by hardware components to communicate serially.[40] SPI is a serial based protocol which is single master multi slave serial based and also fully duplex.

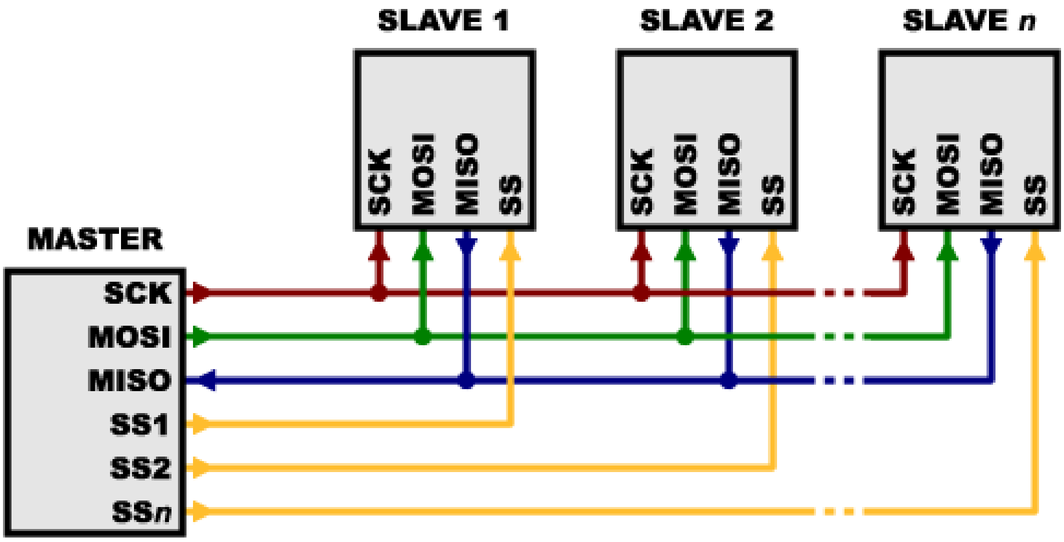


Figure 3.18. Communication between devices in an SPI based communication Source: Sparkfun Electronics Learn official website.

The above Figure 3.18 shows how the communication between the devices occur in an SPI based protocol. The SCK(Serial Clock) line is the clock line from the master which generates clock pulses to manage the communication, Master Out Serial In (MOSI) line deals with the writing instructions from the master to the slave, Master In Slave Out (MISO) deals with the read instructions to the master from the slave where slave writes data onto the master. The Slave Select (SS) lines represent whom should the master communicate with. Figure 3.19 represents how the commands sent are interpreted in an SPI communication standard.

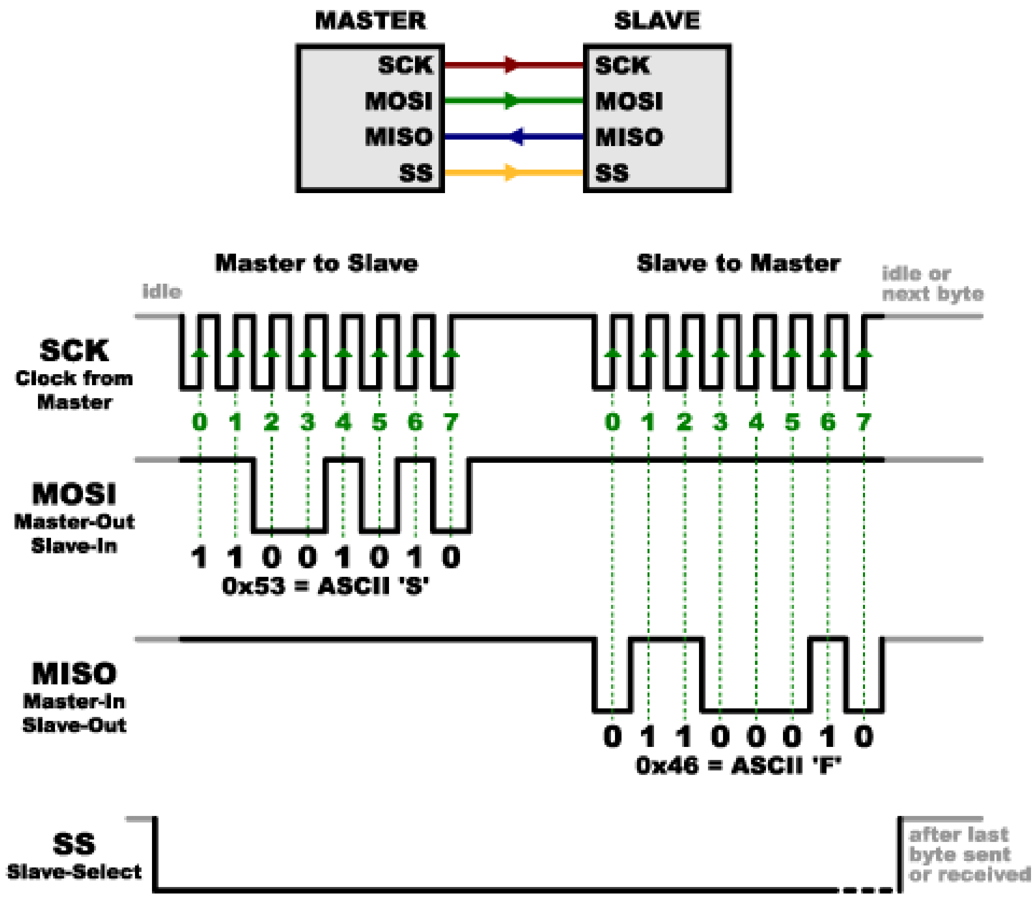


Figure 3.19. Signal interpretation between devices in an SPI based communication Source: Sparkfun Electronics Learn official website

3) UART communication protocol: Universal Asynchronous Receiver and Transmitter protocol deals with serial transmission in a slightly different way than

the above two protocols explained. The main difference is that this protocol is asynchronous which means the protocol does not have a clock embedded in the communication medium. The receiver and transmitter agree upon a desired transmission baud rate(Signals per unit time) so that the receiver knows how much of a sampling rate should it have to ensure that the transmitted signal is received. [41] Figure 3.20 shows how two devices connected with UART communication protocol should be connected.

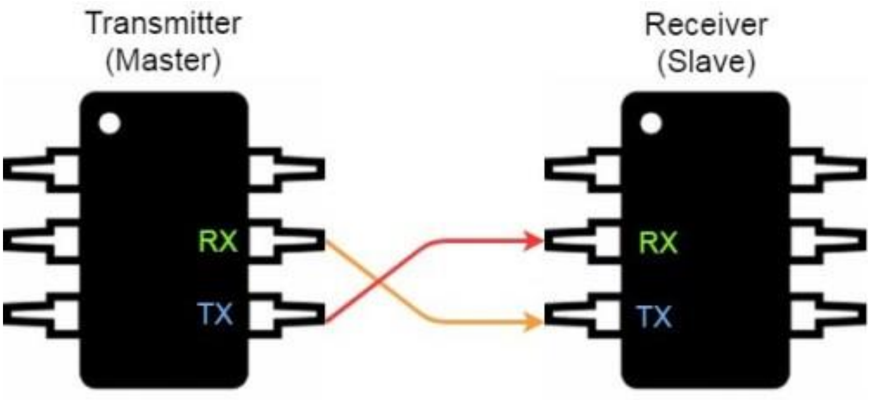


Figure 3.20. Connections in a UART communication protocol Source: Sparkfun electronics learn official website

The RX(Receiving end) terminal of the master is connected to the TX(Transmitting end) terminal of the slave and vice versa. The receiving end receives the data transmitted from the transmitting end. Therefore, this communication is fully duplex. Figure 3.21 represents how a packet send from RX is interpreted after receiving from TX.

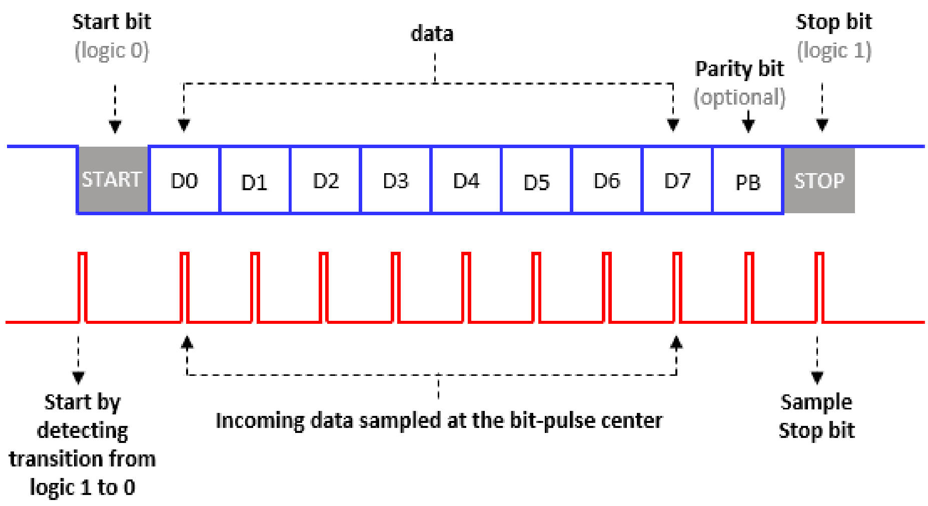


Figure 3.21. Structure of a data packet sent through UART protocol Source: Soliton Technologies official website

UART is one of the most powerful serial communications used in embedded systems and it does not involve much of boiler plate data. (Data which can be deduced without specifically sending) The communication between the Texas instruments CC1310 and Raspberry Pi 3B+ boards and the communication between the Texas instruments CC3320 and Raspberry Pi 3B+ boards use UART communication protocol while Raspberry pi 3B+ and the accelerometer MMA8451 use I2C communication protocol to communicate with each other.

3.3 Calibration of the acceleration sensors

Chapter 3.1 explains how the data is transmitted from the accelerometer sensors through the sensor nodes and finally to the gateway of the network which connects the whole network to the internet. Although the process, when explained projects a feasible solution of the data being transferred to the destination, the trust base on the sensors is too high. Relying on the sensors, trusting that the data obtained from the sensors is correct is not feasible in a research. Therefore, the sensors which obtain the data should be calibrated for their accuracy levels and a few measures should be taken to adjust the readings obtained to get the correct reading with an acceptable error. This process is called calibration of the sensors[42]. In this section, various methodologies of calibrating the sensors will be explained and how the sensors in this system is calibrated is explained.

Calibration of accelerometers can be done using several methods. The most common method is by using the gravity [43]. This method of calibration is feasible for accelerometers with a low accuracy, but for our system due to the highly accurate and sensitive accelerometers, this method is not feasible.

The other highly accurate methods that can be used are, Tilt method and Sine-sweep method[44]. Shaker table is used for this calibration purpose. There are many variations of Shaker table, but all of them serve the same purpose. That purpose is to send a programmable wave and shake the objects that are placed on it according to the wave[45] .

Figure 3.22. Shaker table Source: APS Dynamics official website

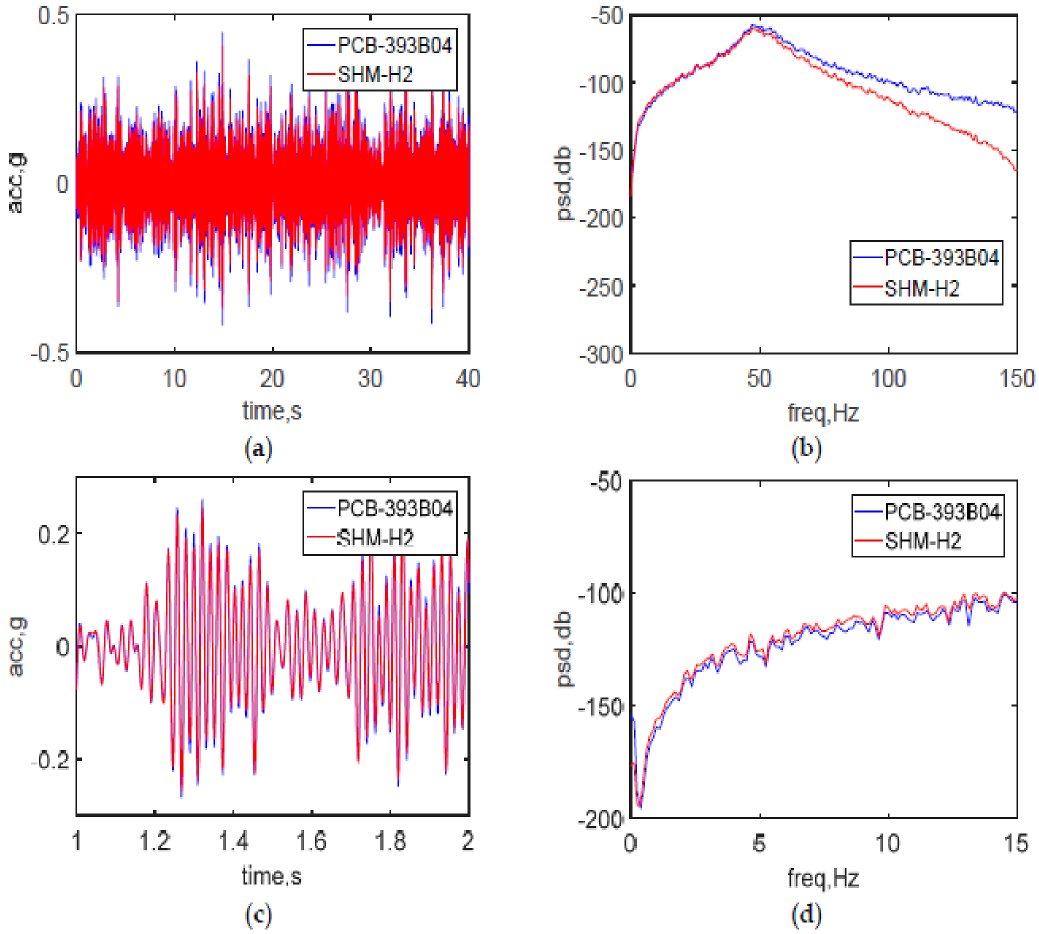
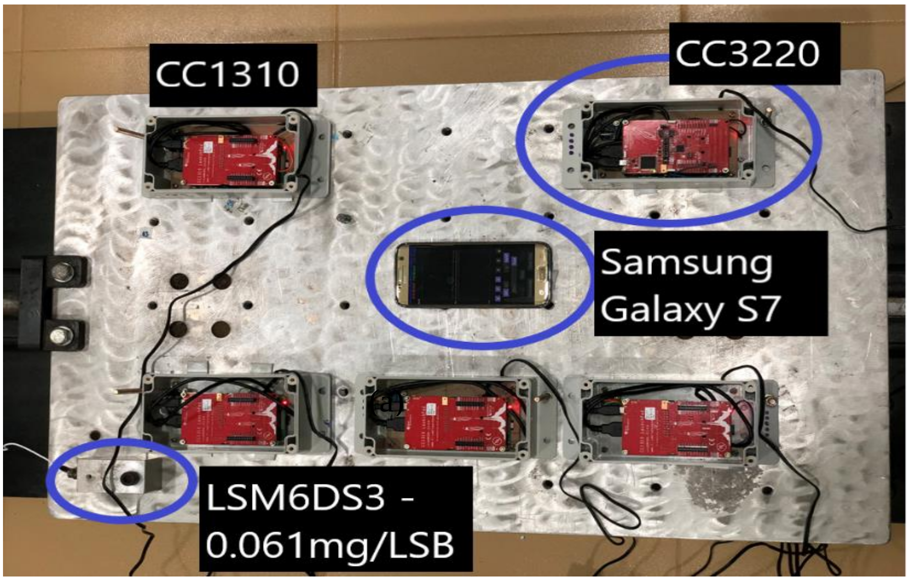


Figure 3.23. (a)acceleration vs time graph using sine sweep method with a calibrated accelerometer and an accelerometer which should be calibrated. (b) Fourier transformation graph of (a). (c) zoomed in graph of (a). (d) zoomed in graph of (b) Source: Available at [27].

The method that is used in our system is called sine-sweep method. In this method, a sine wave is sent with the same acceleration but with varying frequencies. Generally, these frequencies will be continuously increasing to some extent. Then the graph drawn is converted with the use of a Fourier transform function. (Further explained in Chapter 5) Finally the relevant accelerometer and the highly accurate accelerometer relative to which our calibration occurs creates a graph with similar features but with a slightly different variation at different frequency ranges. Then using programmatical methods, our calibration should be done to make sure that both graphs coincide.



(a)

(b)

Figure 3.24. (a)Arrangement of all the accelerometer sensors for calibration (b)Sensor nodes placed on the shaker table

Figure 3.24 shows how our sensor nodes and various accelerometers were placed on the shaker table ready to be calibrated. The sensors that were laid out were,

LSM6DS3: 0.061mg/LSB (The highly accurate accelerometer calibrated and placed on the shaker table)

MMA8451: Accelerometer that is placed inside Sensor nodes.

BMA222 : Accelerometer which is embedded onto CC3220 development board

Accelerometer of Samsung Galaxy S7

When all of these sensors are placed on the shaker table and shaken with a sine-sweep wave and all the data was processed the below graph appeared, Figure 3.25 shows how the graph appeared after the data was fetched.

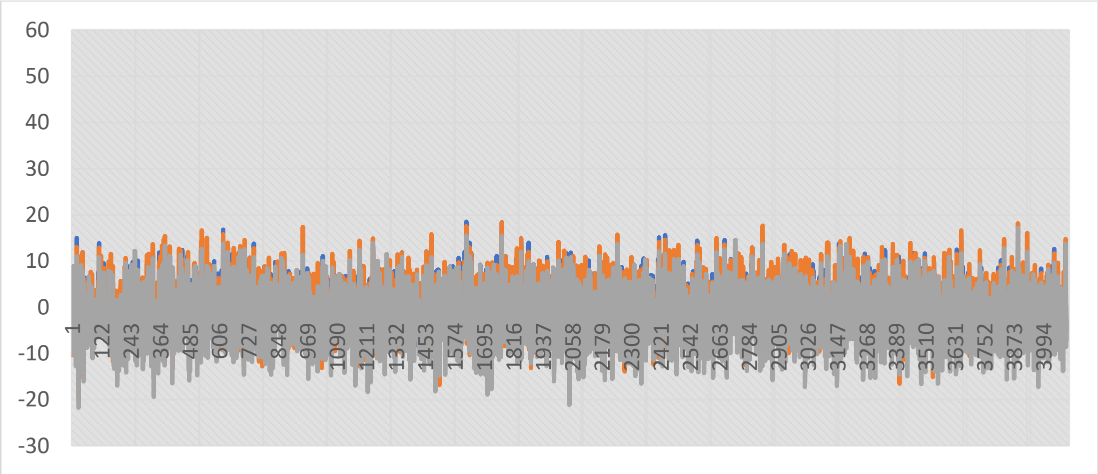


Figure 3.25. Acceleration components of the accelerometers placed in the shaker table

Then a fast Fourier transform was done on this data as in Figure 3.26 and calibrated programmatically to coincide with the shaker table accelerometer. This is the calibration process that was done to our system to ensure that the accelerometer sensors give the correct reading.

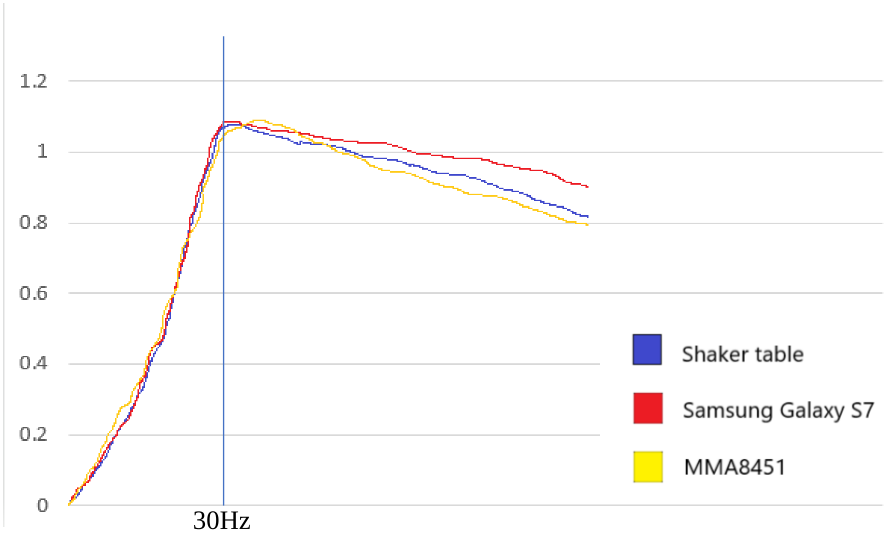


Figure 3.26. The FFT graph drawn using the data obtained during the sine-sweep method

Similar to the z axis calibration MMA8451 Accelerometers were calibrated in the x axis and y axis by rotating them and placing them on the shaker table and applying a sine-sweep wave on them.

3.4 Synchronization of the sensor nodes

With the help of the sections 3.1 and 3.2, the flow of data through the network until the destination is made clear. Unlike simple wireless sensor networks, this system that was developed had an extra requirement which is making sure that all the sensors are synchronized when collecting the data with a minimal jitter at the μs range. Synchronization in this context means that every sensor node starts its process at a specific time. This is a requirement in our system, because of the following scenario. During the data interpretation process, the data from every node is collectively examined and processed[46]. During this process, to identify the phase angle of the motion associated with every sensor node, synchronization is needed. This is further explained in Chapter 5.

The rest of this section explains how synchronization is implemented and maintained in our system with an acceptable error and how is the benchmarked synchronization methodology differ from our methodology. The benchmarked synchronization protocol, Glossy, is a network protocol implemented to control flooding in a mesh network. Flooding is when two different nodes retransmit the same data packet, at slightly different time intervals which will cause collision. To control this flooding scenario, Glossy must make sure that the devices connected are synchronized. Eventually Glossy implements synchronization as a biproduct of its main purpose. [47] Glossy protocol which achieved 0.5µs [47] which as mentioned above is a benchmark for time synchronization. Glossy uses Hardware interrupts with SFD pins[47] but in our system as we do not have that feature in our node, we are forced to use software interrupts. Glossy is a protocol which is radio driven where the radio core and the CPU core are found separately but as our system is CPU driven, this protocol cannot be implemented. Therefore, a variation of this protocol, with the same key idea is implemented in our system.

Our system synchronizes every node, in three steps. For the first step, the transmission delay between two nodes are calculated. Then as the second step, taking the transmission delay into account, the nodes decide the time at which when they should start collecting data exactly to ensure that they are synchronized. Finally, as the last step these steps are repeated after fixed long term intervals to ensure that the clocks maintain the synchronization. These steps are explained further elaborately below.

There are a few key concepts adapted from Glossy to implement the method mentioned above. The most important concept is, having fixed time slots which is consistent across all nodes as shown in Figure 3.27.

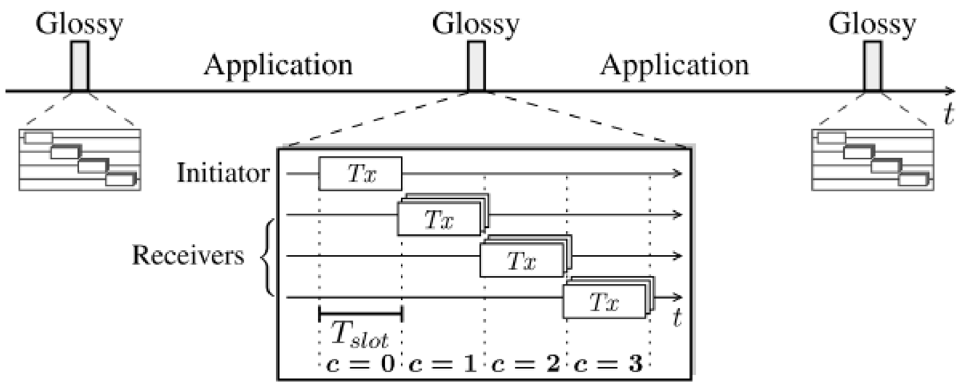


Figure 3.27. Representation of time slots and counter method used in Glossy. Source: Available at [23]

Every node in our system has a fixed time slot programmed in them. This is calculated by allocating equal number of clock ticks for a time slot for every node. The nodes can then interpret the command with respect to the number of the time slot.

Figure 3.28 shown below shows how our system synchronizes the system with the help of the above constant time slot duration concept.

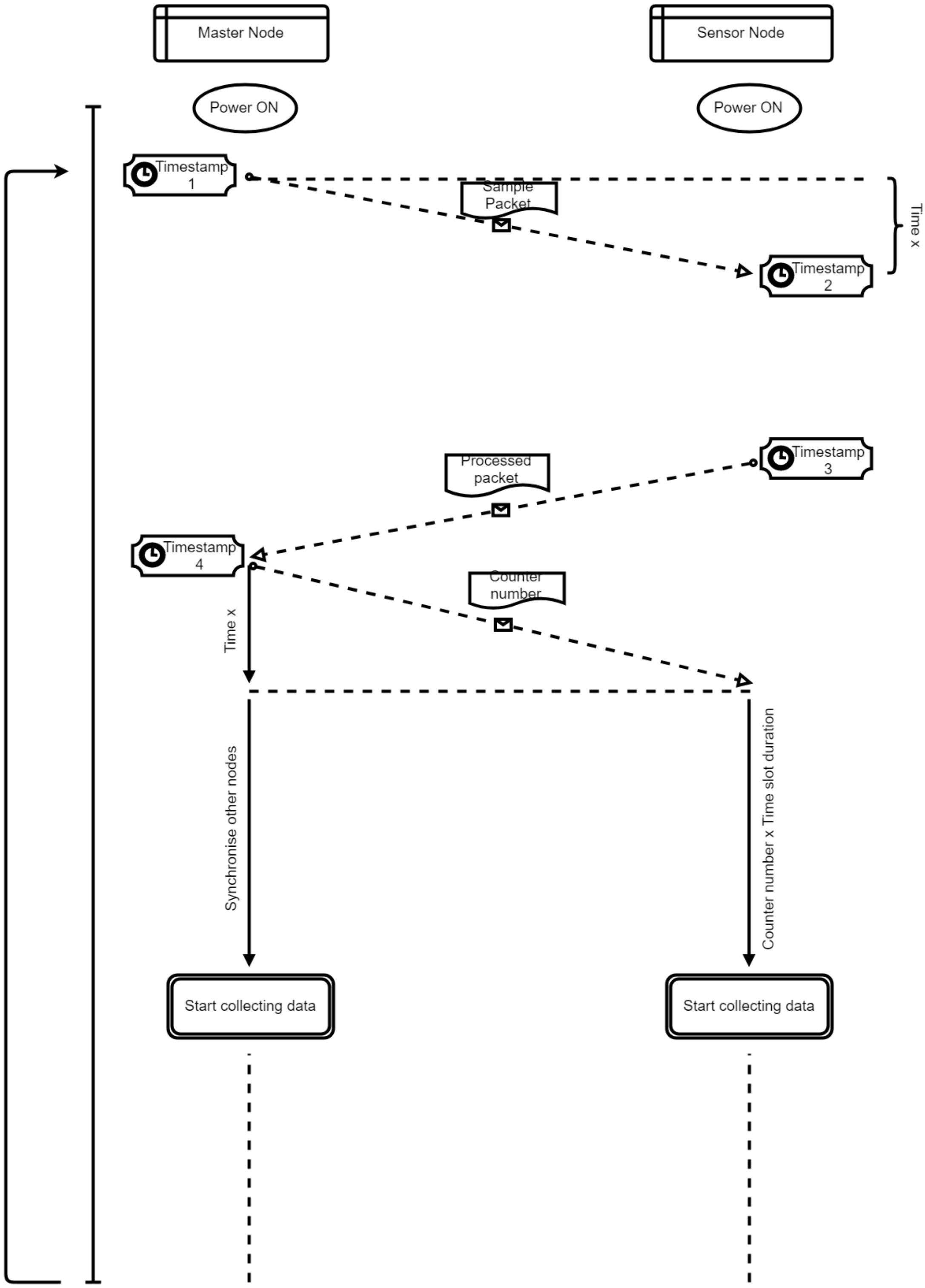


Figure 3.28. Synchronization methodology used in our system

The master node, when switched on sends a sample packet to one of the nodes after storing the timestamp(t1) at which the packet starts its transmission. Then the relevant sensor node which receives the packet, stores its timestamp(t2) when it starts receiving the packet. After the node does its processing with the packet, it is transferred again to the master node. The timestamp at which the packet starts its transmission(t3) is also stored. The packet which was sent contains t2 and t3. The master node stores the time stamp at the time when it starts receiving the packet. (t4) Using the formula,

$$\text{Transmission delay} = ((t4 - t1) - (t3 - t2))/2 \tag{3.1}$$

the master node calculates the transmission delay. Then the master node sends a counter number indicating the sensor node to start collecting data at the specific timeslot after the number of timeslots specified in the counter. The master node calculates the time at which, the master node itself should start collecting the data. In a system with only one sensor the time will be number of time slots specified by the counter deducting the calculated transmission delay. This process is done after specified time limit. For an example the nodes will synchronize and collect data for 45 minutes and then start its synchronization once again. This repeated synchronisation is done to address the drift in the clocks of the nodes.

Figure 3.29. Synchronization simulation used in our system

When the system is scaled, multi hop system should be implemented where the master node synchronizes a slave node and the next unsynchronized slave node which is out of range from the master node is synchronised by an already synchronized slave node. When this process happens, the error of this system is also linearly increased. To address this issue a variation of multi hop synchronization can be used where the master node synchronizes a slave node which is in the range of a single hop and then an unsynchronized node which is in the range of two hops from the master node is synchronized by using a synchronized node as a proxy by synchronized sensing method. This adaptation can be scaled for a great extent as the error remains constant throughout the synchronization process.

The synchronization sessions that were conducted by sampling data from this system is shown using Table 3.3 and Figure 3.29.

$$SD = \sqrt{\frac{\sum(ri - ravg)^2}{n - 1}} \tag{3.2}$$

where: SD = Standard deviation of the synchronization time periods

ri = The specific synchronization time period

$ravg$ = Average of all r_i of a sync session

n = Number of datasets

Table 3.3. Summary of all the synchronization sessions

Session	**Average**	**Standard deviation**
1	50.8	13.83
2	46.1	16.61
3	61.7	23.98
4	56.9	26.59
5	58.2	22.48
6	43.95	19.16
7	40.15	21.24
8	40	15.81
9	38.4	18.04
10	38.5	17.64
11	40.5	16.85
12	42.25	19.72
13	38.75	19.36
14	35.95	13.33
15	33.45	18.38
16	41.2	17.24
17	32.55	16.40
18	35.65	17.34
19	38.1	17.92
20	35.95	17.23
21	40.1	18.92
22	43.4	17.85
23	35.85	19.49
24	37.25	15.68
25	36.65	18.80

CHAPTER IV

4. DATAFLOW OF THE COLLECTED DATA FROM THE SENSOR NETWORK TO THE WEBSITE

The collected data is manipulated, stored and processed in such a way that allows the end user to obtain a meaningful visualization with easy access. The dataflow is given below in the Figure 4.1

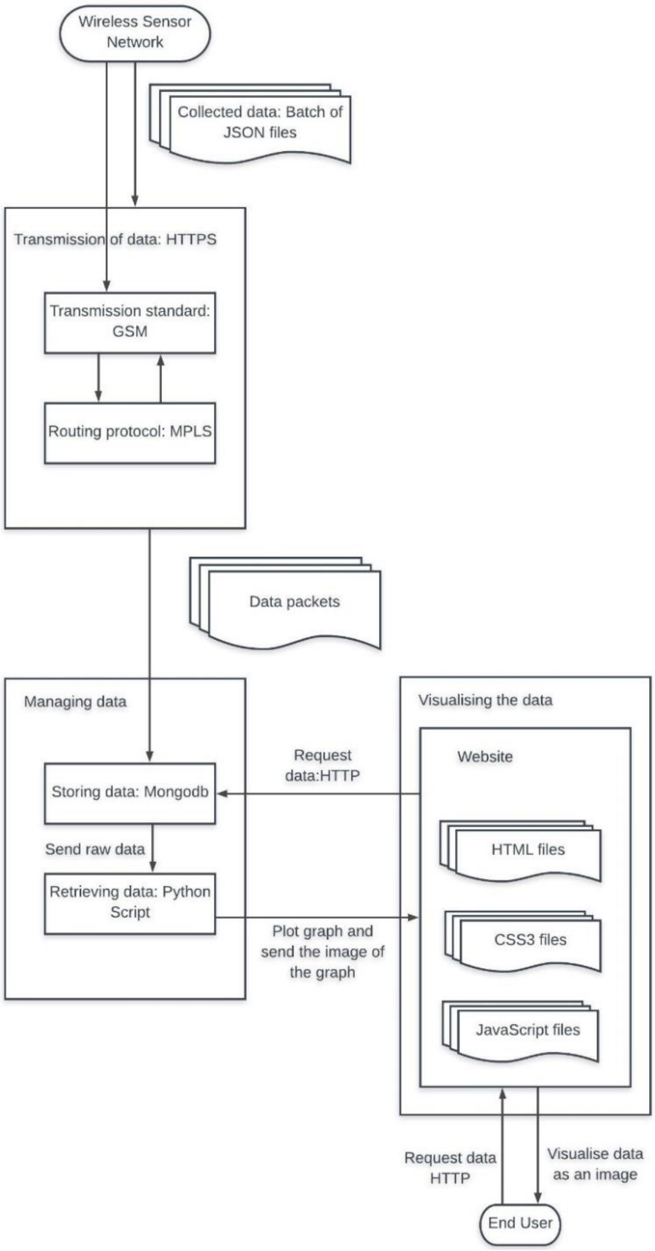


Figure 4.1. The Dataflow of the collected data from the sensor network to the website

4.1 Transmitting the collected data

Data collected from the sensor network established in the civil structures should be transmitted reliably to our data sink. As the data sink was chosen to be a web-based database, the infrastructure which transmits the data is selected to be able to accommodate the web-based communication. Web based communications occur through packet based routing.[48] Routing is a methodology which specified the path a data packet should traverse to arrive at its destination. Packet based routing standardizes the way in which a data packet should be transferred from one place to the other. The below Figure 4.2 illustrates how a packet is routed through a network to arrive at the desired location.

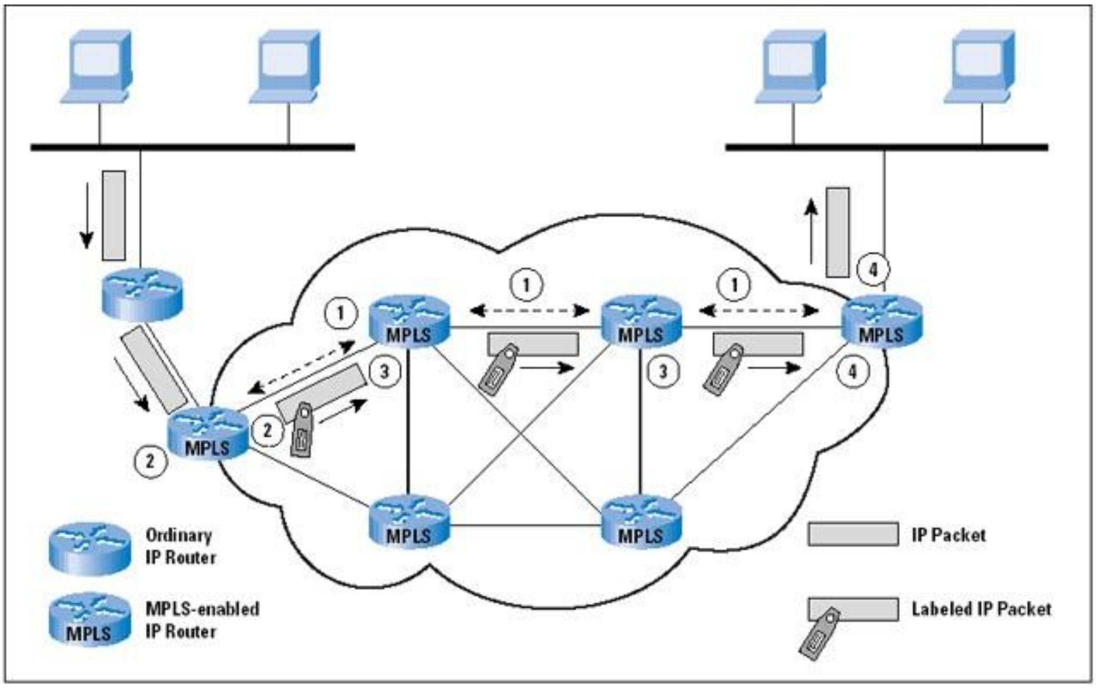


Figure 4.2. A routing standard MPLS (Multi-Protocol Label Switching) Source: Cisco official website available at The Internet Protocol Journal-Volume 4 Number 3

The packet needs to be transmitted using a suitable transmission standard. Global System for Mobile Communications (GSM) is chosen out of GSM, NB-IoT and LoRaWAN.

4.1.1 The infrastructure used for the transmission of data

All these telecommunication standards can use the same infrastructure but needs different dedicated modules to send and receive data. The infrastructure for these telecommunication standards consists of three tiers. The separation of these tiers is represented by Figure 4.3.

The first tier is the set of terminals which are the devices used to send and receive data. The second tier consists of base stations and base station controllers. After dividing the geographical territory into small Geographical Service Area (GSA), a base station is assigned to each GSA to accommodate all the device terminals in that GSA[48]. These base stations are then controlled by a BSC(Base Station Controller) to manage several functionalities of the network.

Using such small cells ensures that a wide range of devices to be connected to the network by reusing the frequencies at which the data is transferred in non-neighbouring GSAs. Figure 4.4 represents the frequency reuse which is used by the GSAs to facilitate higher number of nodes to be connected to the system. The third tier which is the Network Sub System (NSS) manages the connectivity between wide ranges of BSCs and also helps with the switching of the data. Switching is directing the data packet received to the next handler until it reaches its destination. The overview of the whole infrastructure is shown in Figure 4.5.

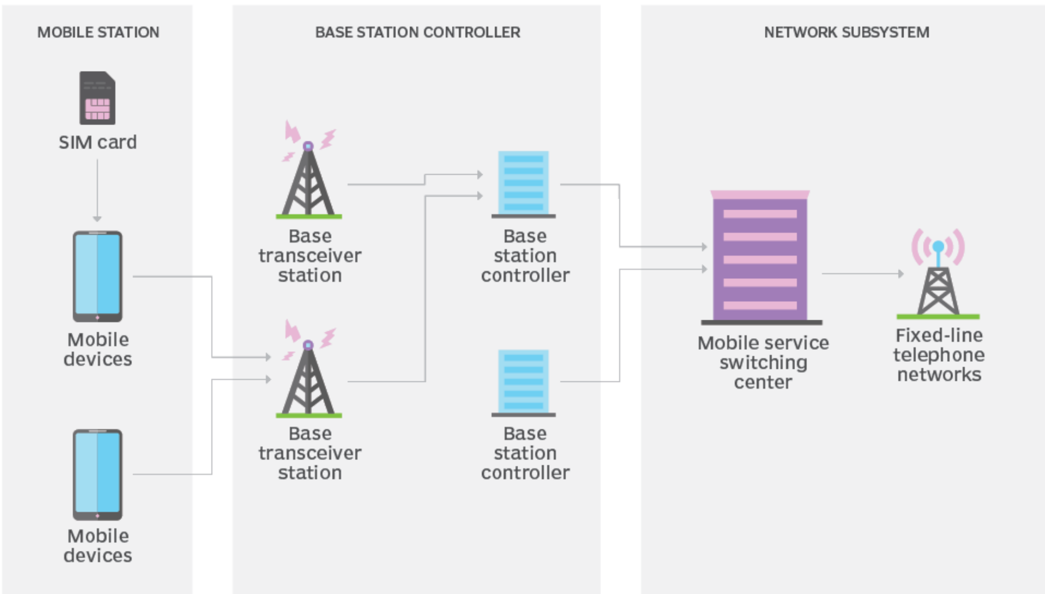


Figure 4.3. Three tiers of the telecommunication infrastructure used in our system. Source: Pump official website available at Cellular networks 101.

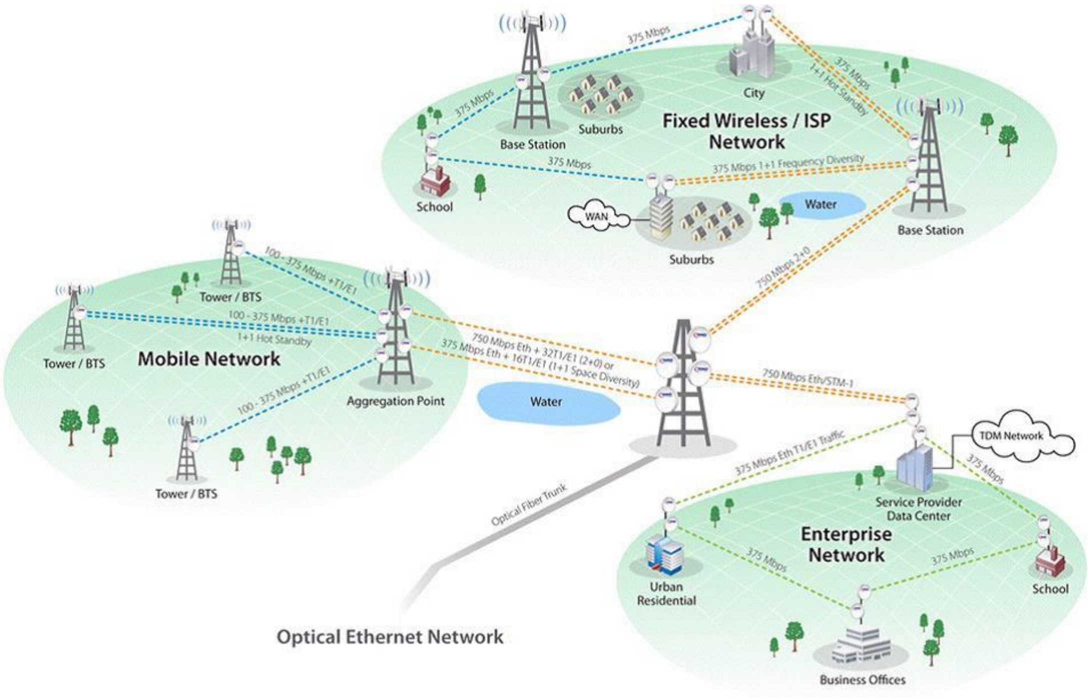


Figure 4.4. The overview of the telecommunication infrastructure used. Source: Pump official website available at Cellular networks 101.

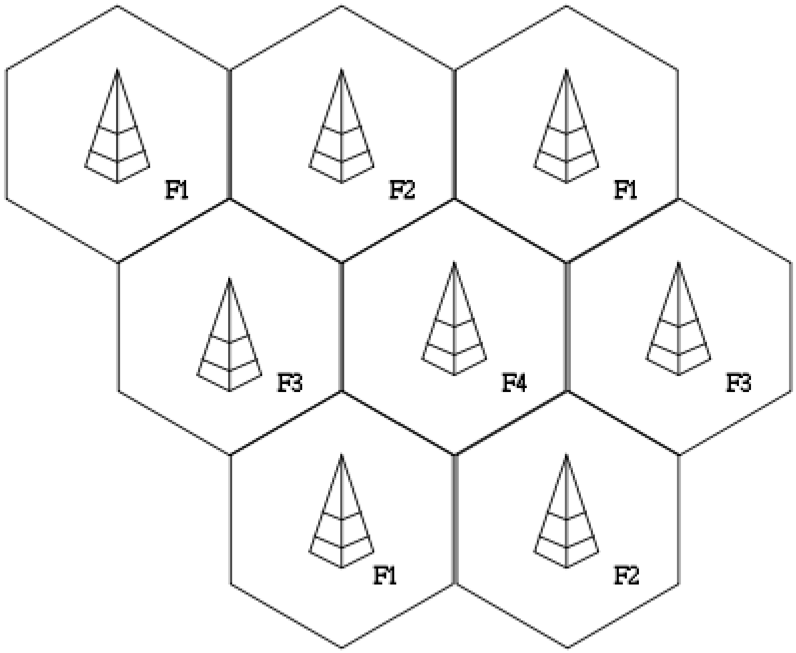


Figure 4.5. Representation of GSA and frequency reuse. Source: Wikipedia official website.

4.1.2 Selecting the suitable communication standard for data transmission

There are several transmission standards which could be used with the above infrastructure. These standards are GSM, NB-IoT and LoRaWAN.

Global System for Mobile Communications (GSM) is one of the oldest telecommunication standards that we have used and still present. This standard is mainly used for voice but sending data in the form of General Packet Radio Services (GPRS) and Short Message Service (SMS) is also possible[49][50]. In present context due to Voice over Internet Protocol (VoIP) and the need to have an infrastructure dedicated to voice in analog format is becoming obsolete[51]. Therefore, GSM is being optimized for the use of data communication. This telecommunication standard has a range of about 35km.

Narrow Band IoT (NB-IoT) uses the same infrastructure mentioned above and uses unused GSM channels. The range of this telecommunication standard is about 10-15 km[52].

LoRaWAN is a telecommunication standard which is also known as Low Power Wide Area Network (LPWAN) is a low power telecommunication standard which has a range of about 5-10 km[53]. This telecommunication standard is used for IoT applications and still in the process of being introduced to various corporations and institutions[52].

Even though NB-IoT and LoRaWAN were technologies developed to facilitate IoT (Internet of Things) applications, GSM technology proved to be effective in the present context because of its wide user range and the infrastructure developed is optimized to be used with GSM with time. NB-IoT and LoRaWAN consumes less power than GSM, but the cost savings due to the optimizations, the cost savings due to the cheaper GSM module and the high availability of GSM receivers facilitates GSM to be the most effective telecommunication standard that NB-IoT and LoRaWAN.[54].

4.1.3 Selecting a suitable format for transmission

When storing data in the database, the format to store the data was decided. There are several formats to store data. The traditional format for data transfer is Extended Mark-up Language (XML). In our system, the data transfer is done as (JavaScript Object Notation (JSON) objects.[55] The use of JSON objects instead of XML objects is because JSON objects are objects which is directly based on JavaScript while XML is based on Standard Generalized Mark-up Language (SGML) and JSON objects are designed to carry low weight payload while an XML data structure is designed to carry varying size payloads. The system that we develop needs a low weight record with constant size. This makes using JSON format for managing data the most suitable choice.[56]

4.2 Managing the mass collected data

The collected data should be stored at a location for it to be accessible to use it for simulations or visualization purposes. When managing a huge amount of data, we should make sure the data is continuous to be able to analyze in the time domain and the data is available and easy to retrieve whenever requested.

4.2.1 Storing the raw data for easy access

For the storage of data, a suitable database system should be chosen. A database system is a collection of one or more computers which are designed to store, retrieve, update and delete data in an efficient manner. A Structured Query Language(SQL) is a language which can be used as a "declarative query language"(which can create, insert, update, delete and query information), "Data Definition Language(DDL)"(which defines the structure of the data stored and restricts access for unauthorized users) and "Data Manipulation Language"[57]. Several factors should be considered when choosing such a language for a specific system. A few of those factors are

1. Whether the database is consistent across the access points
2. Whether the database is partition tolerant
3. Whether the database is always available.
4. Proprietary or an open source database
5. Whether the database is in the cloud or whether it is self-hosted
6. The data model of the database
7. The amount of data we hope to deposit in the database

8. The amount of data generated per unit time
9. The speed of retrieval

After a significant amount of consideration, the database MongoDB which uses a query language called Not only SQL (NoSQL) was chosen instead of the traditional SQL dependent languages such as MySQL because of several factors[57][58].

1. Dynamic Schema: The format of the data deposited can be unstructured without the need of having a specific data schema.
2. Auto-sharding: This is sharing multiple servers for storage of data
3. Replication: Having replicated data in the database enables a NoSQL database to have reliability. This enables the database to have a copy of the same data which can be recovered if some part of the database fails.
4. Integrated Caching: Caching is the ability to store the information that will be needed in near future for easy retrieval.

4.2.2 Storing the data in a suitable data schema

A data schema is how raw data is stored in the database. The NoSQL format does not require a record (A row of data) to be in a proper data schema. The records may have varying number of columns as the rows are stored as different objects. Even though this does not ensure the need to maintain a proper data schema, it should be maintained to a certain extent to be facilitate easy identification of data. Considering these reasons, a proper data schema was chosen with predefined fields.

The fields in a record in our system are,

Node :The number of the node from which the data was taken

Timestamp :A universal notation which can be decoded into identifying the date and the time at which the data was collected in the node.

X :The raw acceleration in the X direction

Y :The raw acceleration in the Y direction.

Z :The raw acceleration in the Z direction.

This data schema allows a query to be processed properly and can ensure that the data collected can be retrieved as long as the user who made the query knew the data schema.

Therefore, all the records are stored in our database with the use of the above data schema in JSON format.

4.3 Creation of a website

A datalogger is needed for the storage for mass produced data in a data acquisition system. Dataloggers are electronic instruments which facilitate data inputs at a very high frequency. Using a traditional datalogger proved to be very expensive, therefore web based datalogging was chosen for the storage and the visualization of data. The Figure 4.6 below shows a datalogger which can get up to 4 simultaneous analog inputs and 4 digital IOs for Triggers and Alarms, can plot real-time Fast Fourier Transform graphs for monitoring. This data logger costs 1499USD. Web based data logging does not require such an amount of investment and is easily scalable as the number of the nodes increase. A detailed cost comparison is denoted in Chapter 5.

Figure 4.6. WebDAQ Vibration data logger. Source: Microdaq official website

A datalogger would generally cost from 540USD to 1800USD in the present context, but a web based datalogger would not cheaper and the architecture of the web-based applications will have numerous ways of enhancing the system.

4.3.1 The architecture of a web-based platform

When opting for a web based data logging, client-server architecture should be used for the purpose of requesting and responding[59].

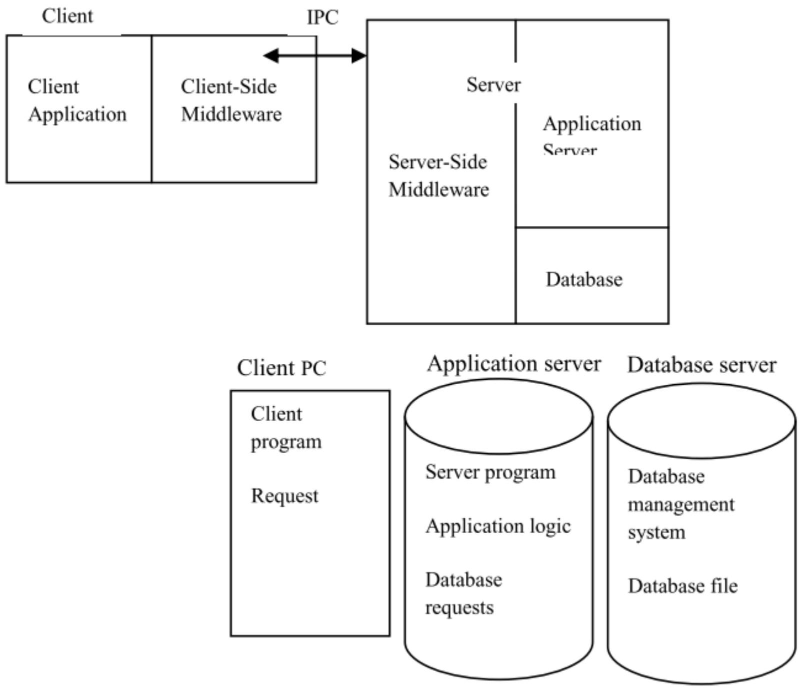


Figure 4.7. Client Server Architecture from [12].

The process of fulfilling a command through the web happens through sending and receiving request and response objects. Usage of protocols such as Hyper Text Transfer Protocol (HTTP) and Hyper Text Transfer Protocol Secure (HTTPS) are prominent across system that is used in this research. Usage of HTTPS protocol is when the data is sent from the sensor nodes to the database to ensure secure transfer and the usage of HTTP is used throughout the website
For an example, when a query is made from the end user of the website requesting the visualization of the data gathered an HTTP request object is sent to the server requesting the image of a graph drawn for a particular time slot which will then be

answered by an HTTP response object containing the image, if the image is available and the request is valid [60].

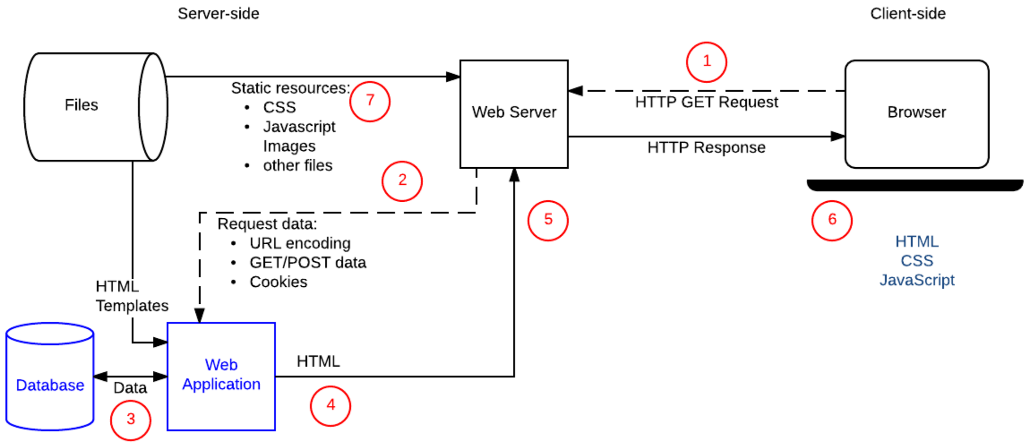


Figure 4.8. HTTP request and response flow. Source: Mozilla Developer Network official website available at GitHub

Due to these reasons it was decided that the data gathered should be displayed in a website to make sure the data was visualized after pre-processing and post-processing.

A Linux based server is used for this purpose as a server for this project. The specifications of the server are given below.

CPU:2

RAM:2GB

HDD:16GB

Guest OS: Ubuntu 18.04 LTS x64

4.3.2 Web-based technologies used in the system

Several technologies should be used to make sure the website is functioning properly. HTML, CSS3, Bootstrap, JS, jQuery, Bootstrap, API were the technologies used for the website to function properly.

Hyper Text Mark-up Language (HTML5) : This is a standard way of tagging elements such as text or multimedia to be displayed [61].

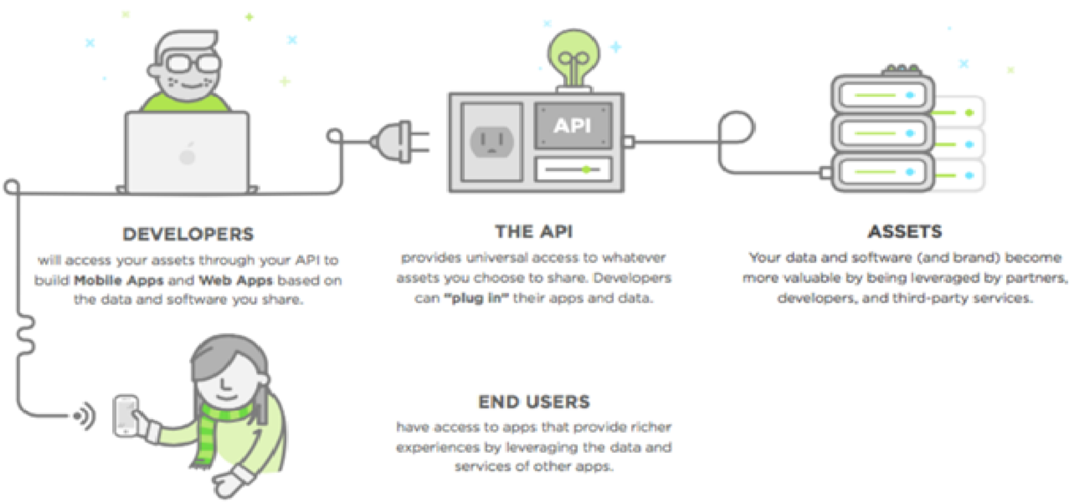
Cascading Style Sheets (CSS3) : The standard way of referring to the tagged elements to change the attributes to render in the webpage such as text size, background color etc[62].

JavaScript (JS) : A web based scripting language to add functionality to address the changes for various events[63][64].

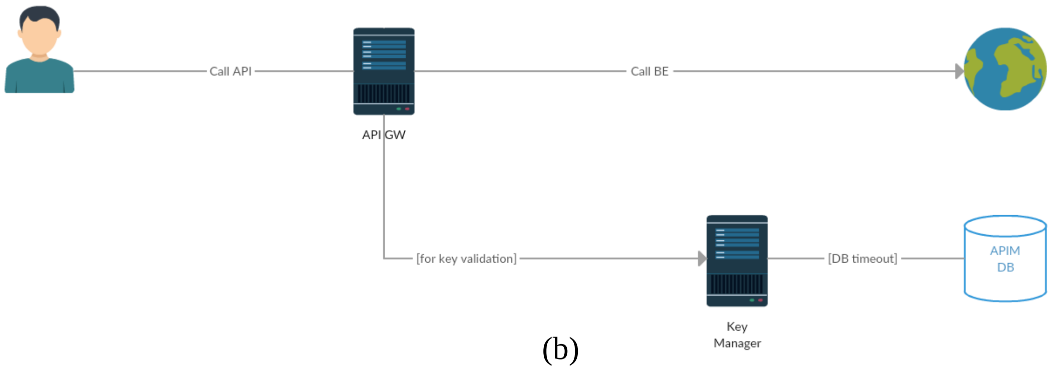
jQuery : A Javascript library designed to manage and manipulate the tagged elements of HTML and handle events in an efficient manner[63].

Bootstrap : A CSS framework which has predefined designs for tagged elements considering their functionality and their purpose[65].

API calls: Application Program Interface is an interface between two web portals. We can make an API call with the use of jQuery and specify our API key given to validate the credentials of the user and get a function done in another third-party web portal. We have used this to render the map of the earth and locate every place where our system is located[66].



(a)



(b)

Figure 4.9. (a) API explained Source. Source: Intro to API and what is an API available at Upwork official website (b)An API call with API key validation. Source: API manager available at WSO2 official documentation website

The expected result was gained using all these technologies put together. Several other functionalities were added to the website such as the displaying the details of the team members, displaying the overview of the system and detailed descriptions, displaying all the locations where this system has been placed, offering a portal to send queries about this system and visualizing the data that was requested from the user in the form of an image.

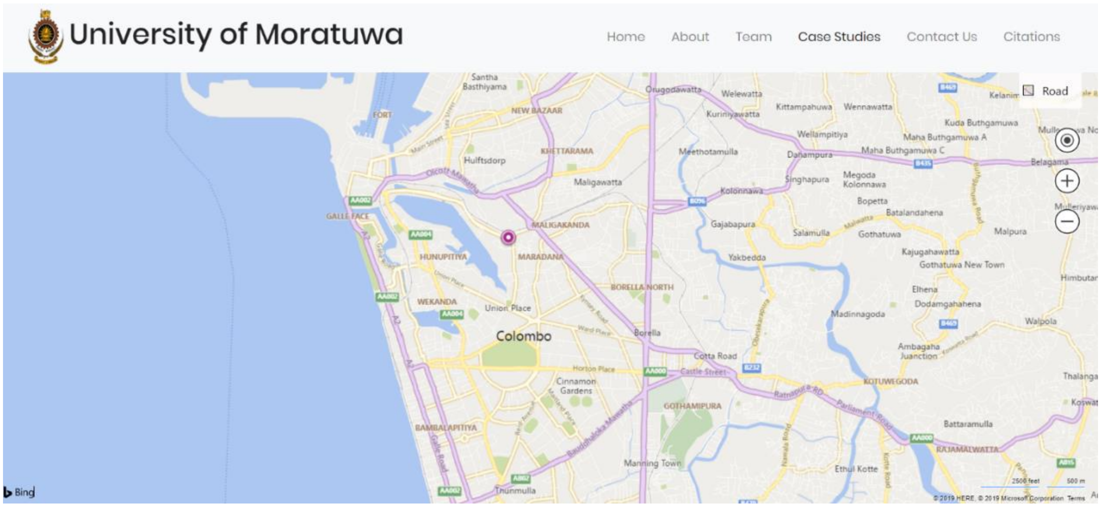


Figure 4.10. A map rendered displaying the locations of mass structures at which our system is placed

4.3.3 Visualization of data

Due to the availability of a website to visualize data which will be rendered onto the computer of the user requesting the visualization, the next step that was undertaken is to obtain the data from the server and to plot it in a graph after post-processing it.

The first attempt to retrieve the data proved to be inefficient due to the large amount of data. The data logged in our database is retrieved with the help of a JavaScript function which calls the data from Mongodb and plots it in 2 graphs and simulates the building model to incorporate the movement of the actual structure. The webpage, when the data was requested started to render for a few minutes because of the huge amount of data retrieved from the server.

After a few attempts a JavaScript function was called to be executed in the server which contains the database which plots the graph in the server itself which is much quicker as the data does not need to be transmitted from the server to the end users' terminals. The graphs were plotted in the server and sent as an image to the requested end terminal which will display the image of the graphs. The data needed for the simulation is also sent from the server which is very low in amount and the user's terminal obtains the data and does the simulation as requested.

These simulations and graphs are drawn with the aid of a JavaScript library called P5.js which facilitates visualizations[67]. The Figure 4.11, Figure 4.12 and Figure 4.13 shows the visualizations of the collected data.

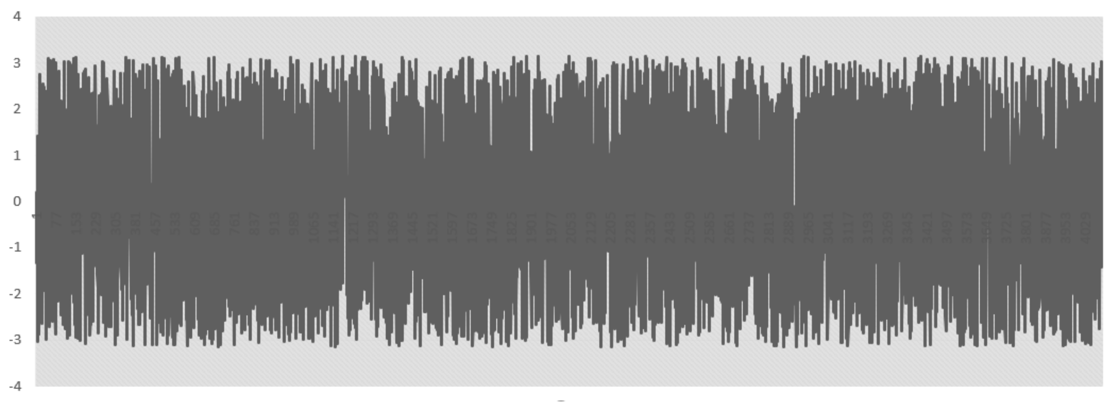


Figure 4.11. An example of the raw data collected displayed in the website

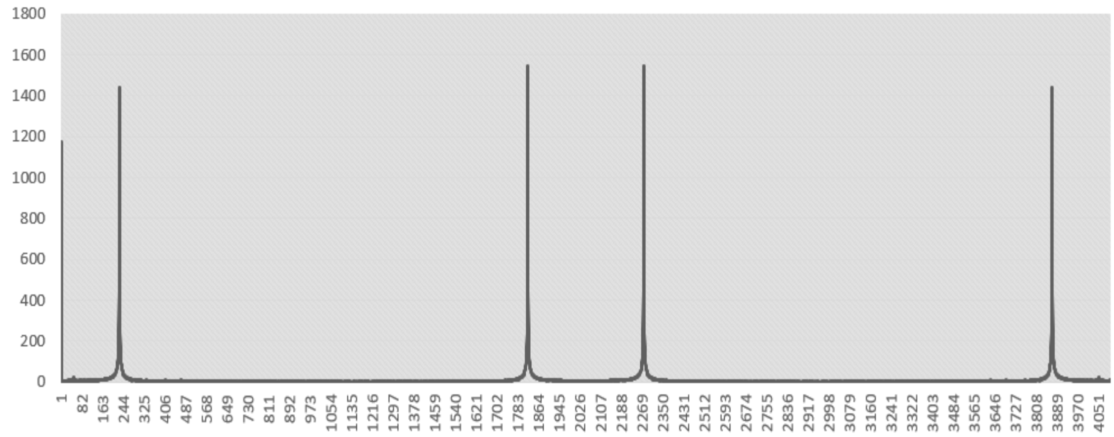


Figure 4.12. An example of the graph denoting the frequency, obtained after applying Fourier transformation on the raw data.

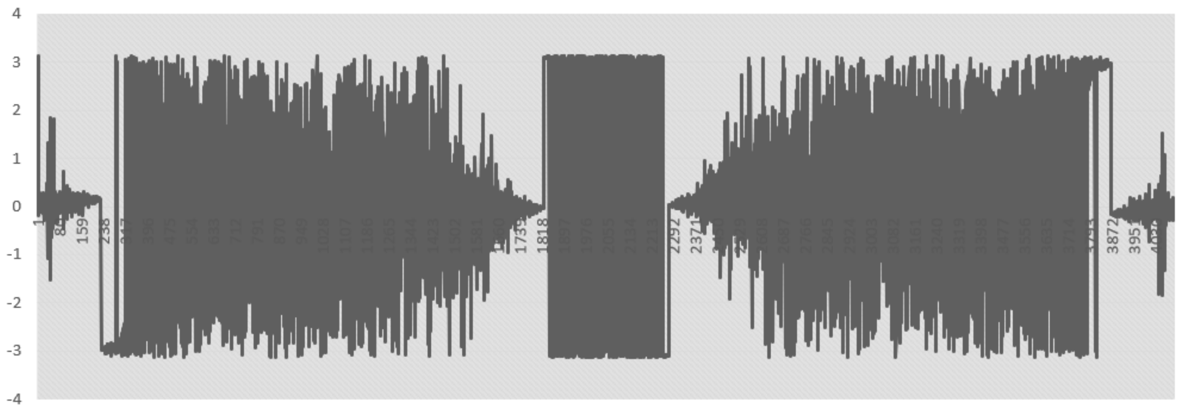
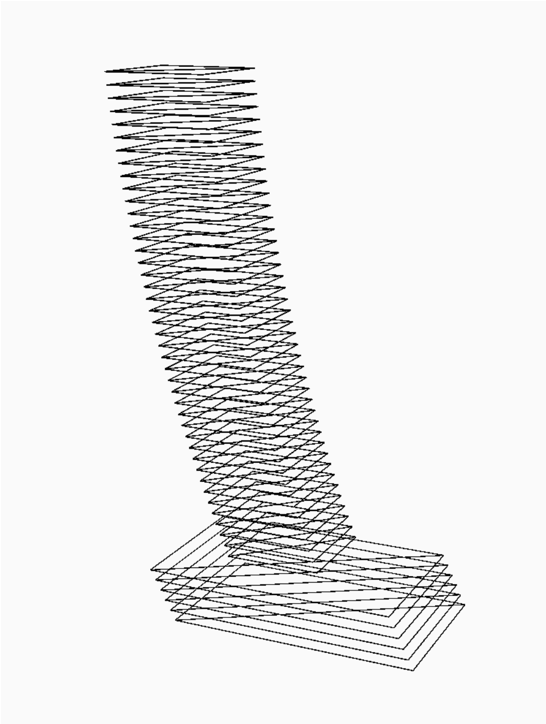
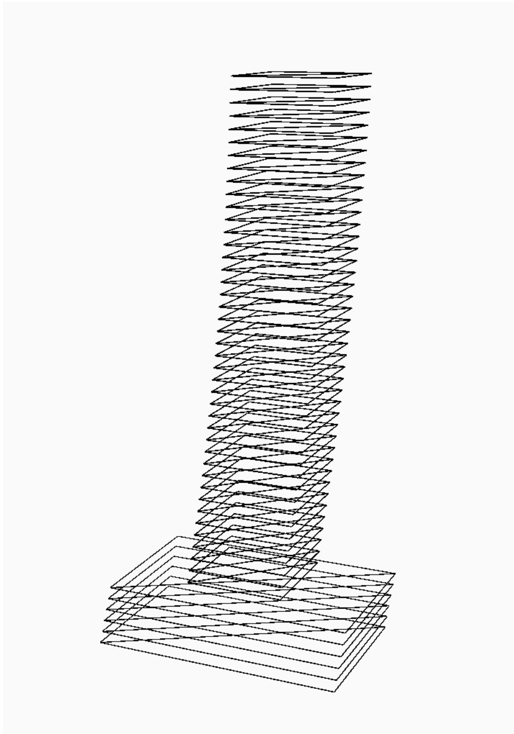


Figure 4.13. An example of the graph denoting the phase angle, obtained after applying Fourier transformation on the raw data.



(a)



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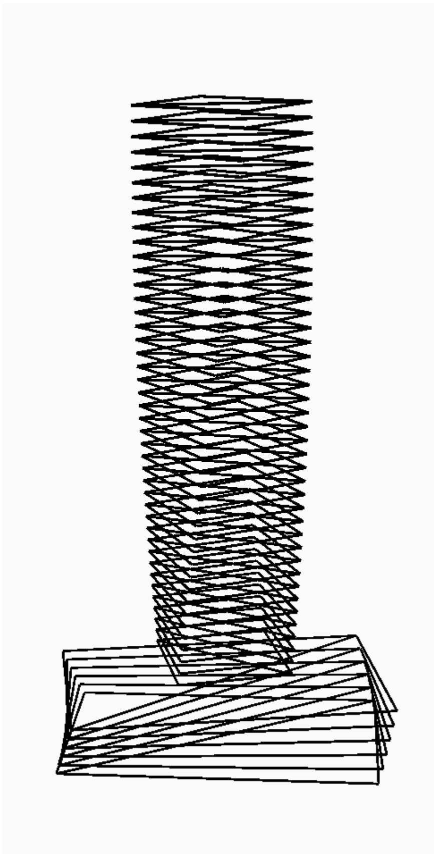


c

Figure 4.14. Simulated diagrams generated by the website (a)Translation along the x axis. (b)Translation along the y axis (c)Torsion with respect to the z axis.

CHAPTER V

5.0 Cost Comparison of Structural Health Monitoring Projects

When analysing a Structural Health Monitoring project, one of the key components of analysis is the effective cost of the system. The effective cost implies the amount spent on establishing and monitoring the system deducted from the amount saved due to the system. This effective cost is calculated by a Cost-benefit analysis.[68] In structural health monitoring projects, the benefit of the system being in place cannot be accurately calculated, but the applications are numerous, therefore the benefits are very high. Therefore, instead of measuring the benefit of the system, only the cost is measured. When determining the cost of such a system, several factors such as the installation cost per node, the cost to make the system, energy consumption per node, the cost of to make a node, the cost to maintain the system and the cost to monitor the system etc. should be considered to make a proper comparison[69].

When measuring the cost of a Structural Health Monitoring project, every structural health monitoring project can be made efficient and accurate with the use of more nodes, therefore, to effectively compare the cost of every system, comparing the cost of a node of each project. Several such comparisons have been made until present with a comprehensive survey[70][71].

5.1 A review of similar systems and the costs associated with the nodes of the system

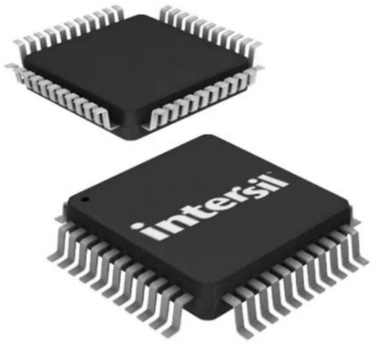
This chapter introduces several projects which have attempted similar objectives such as ours and compares the costs associated with every project and explains various cost reduction methodologies to be adapted by this system in the future to make the system more efficient. The conclusion of this chapter summarizes the costs of every systems explained. A node of a structural health monitoring project would generally have a microcontroller to collect the data, a microcontroller embedded with a telecommunication module to transmit the data, 3 axis accelerometers to determine the accelerations acting on the specific node and other hardware components for the security of the node in the point of view of an electronic system and the mechanical security to ensure the nodes are not damaged. In this chapter only the cost associated with the functionality of the node is compared.

5.1.1 A modular based, real time embedded system to monitor structures

Extreme conditions such as earthquakes, hurricanes and other natural disasters has become a major threat to civil structures throughout the world. The Earthquake occurred in Northridge, California in 1994, in Kobe, Japan in 1995 and the hurricanes Andrew and Iniki of 1989, proved that the need of having a real-time structural health monitoring is of utmost importance as these natural phenomenon having an unpredictable occurrence will pave the way to damage to properties and an loss of lives in an immense scale.

(a)

(b)



(c)

(d)

Figure 5.1. (a) A similar ADC converter DC1151A similar to Hi7188 ADC converter Source: Digikey official website (b) Motorola 68HC11 development board Source: Mouser electronics official website (c) Hi7188 Microcontroller chip Source: Mouser electronics official website (d) 3 axis high precision accelerometer Kistler 8352A2 Source: Kistler official website

A multi-disciplinary program which combined mechanical, electrical and civil engineering departments conducted at Stanford University, developing a hardware platform with embedded systems and wireless sensor networks facilitates such a real time monitoring system.[72] The nodes are said to be low in cost, unobtrusive and maintainable. The costs associated with a single node is listed below in table 6.1.

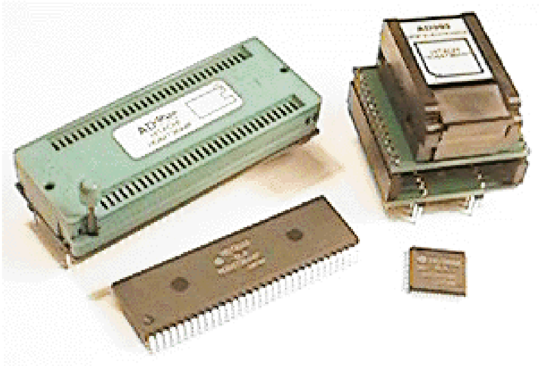
Table 5.1. Cost associated with the components of a node of the system; Straser and Kiremidjian et al. (1998)[72]

Part of the node	Cost per unit (in USD)	Quantity	Total cost (in USD)
A similar ADC converter DC1151A	200.00	1	200.00
Motorola 68HC11 development board	10.50	1	10.50
Hi7188 Microcontroller chip	13.00	1	13.00
Kistler 8352A2	375.00	1	375.00

The cost to make one node of the above type in the present context is 598.50 USD.

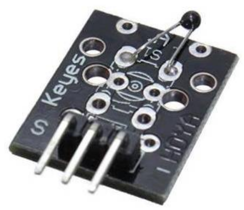
5.1.2 Structural Health Monitoring in highways

Highways are a stretch of civil structures made up of repeating structures. The need to reduce the cost of a single structure is very high as it will increase the efficiency of the material used to construct the highway. The need to examine the health of the highway is also of much importance as it will predict the need for maintenance without relying on time-based maintenance. A highway structural health monitoring of the highway was developed and implemented in UK in 1999. The study was conducted with the help of wireless sensor networks as having wired sensors in a highway is very expensive due to the sheer magnitude of the highway. Unlike other projects which just measured the accelerometer readings to plot the modal shapes and predict the damages, this project was conducted using temperature sensors as well which measured the road base and the surface temperatures at the site.[73] The cost associated with a single node of this project is given below in Table 5.2.



(a)

(b)



(c)

(d)

Figure 5.2. (a) Hitachi H8/329 microcontroller. Source: MQP electronics official website (b)Radiometrix RF module 418MHz Source: Radiometrix official website (c) Analogue thermistor module KY013 Source: Thermistors available at Domoticland website (d)SGA series analogue strain gauge signal amplifier. Source: Omniinstruments official website

Table 5.2. Cost associated with the components of a node of the system; Bennett et al. (1999)[73]

Part of the node	Cost (in USD) per unit	Quantity	Total cost (in USD)
Hitachi H8/329 microcontroller	24.99	1	24.99
Radiometrix RF module 418MHz	74.26	1	74.26
Analogue thermistor module KY013	1.37	2	2.74
SGA series analogue strain gauge signal amplifier	244.31	2	488.62

The total cost associated with a node of the above specifications is 590.61 USD.

5.1.3 Designing a wireless sensor unit for a smart civil structure

Various researches were conducted in the early 2000s to ensure that the need of wire based structural health monitoring is made obsolete. Various researches were conducted to design wireless sensor networks and the properties that the wireless sensor network should have to be able to implement and get a result with the required accuracy and sensitivity [74][75][42]. Some research conducted with the same hardware specification of the wireless sensor network is given below.

The cost to make one node of the above type in the present context is 389.06 USD.

The above descriptions are for few of the various projects that had been implemented in the past years in the field of structural health monitoring using wireless sensor networks.

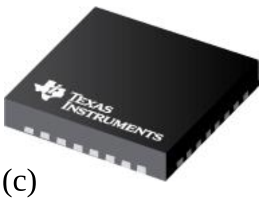
Part of the node	Cost (in USD) per unit	Quantity	Total cost (in USD)
Proxim Proxlink PL modem  (a)	349	1	349
ADXL345 similar to ADXL210  (b)	19.59	1	19.59
Texas Instrument ADS8167 ADC convertor  (c)	3.95	1	3.95
Atmel Atmega256 Microprocessor  (d)	16.52	1	16.52

Figure 5.3.(b) ADXL345 Accelerometer sensor. Source: Amazon official website (b) ADXL345 Accelerometer sensor. Source: Amazon official website (c) Texas Instrument ADS8167 ADC convertor. Source: Alibaba official website (d) Atmel Atmega256 Microprocessor. Source: Ebay official website.

5.2 Cost analysis of a node of this system

The system that was developed with this project is of low cost than most of the projects that had been implemented until now. This is because of several factors. Choosing a low-cost data logging and data management methods using a web base which also adds scalability to a very high extent is one of those main reasons. Such factors have decreased the cost of the whole system by a considerable amount but as we have compared all the other systems with the expense to create and manage a node, the cost of a node of our system is explained in detail below in Table 5.3.

Figure 5.4. Outer appearance of the node of this system

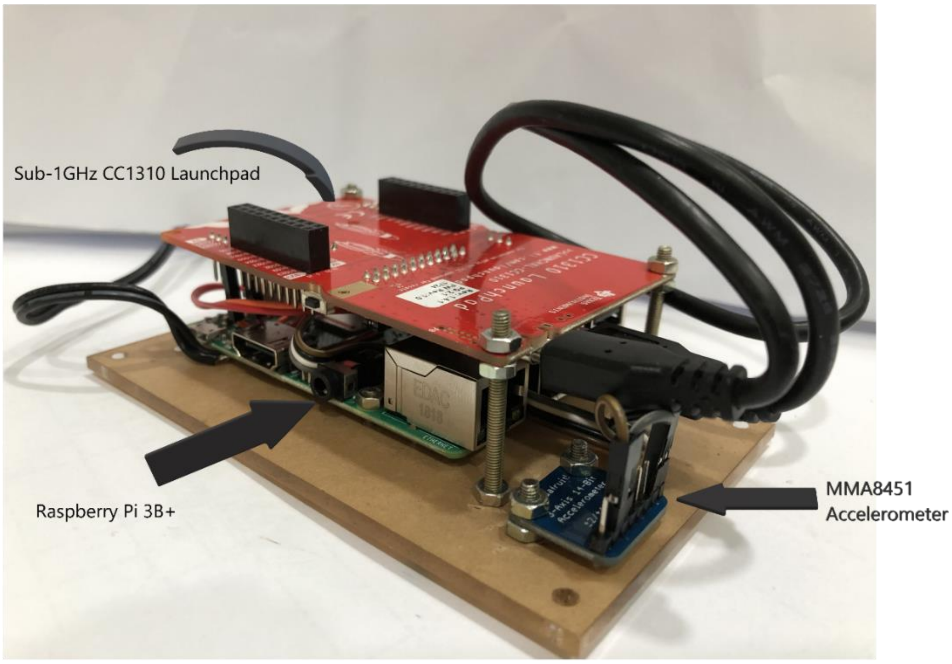


Figure 5.5. The arrangement of the components inside the project enclosure of a node

Table 5.3. Cost associated with the components of a node of the system; Lynch et al. (2001, 2002a, 2002b)[74][75][42].

Component of the node	Cost of a unit+ tax (in USD)	Quantity	Total cost+ tax (in USD)
Raspberry pi 3B+	35.00	1	35.00
Sub-1GHz CC1310 Launchpad	29.00	1	29.00
MMA8451 Accelerometer	7.95	1	7.95
81-MXFR01JA1000 cable	21.83	1	21.83
712-ANT-868-CWHWRRPS	11.17	1	11.17
32GB microsd card	9.34	1	9.34

The total cost of one node is 114.29 USD. The comparison of the cost of the nodes of the projects explained above and our system is given below in the below Table 5.4.

Table 5.4. Cost Summary

Project	Cost of a node (in USD)
Node of this system	114.29
Straser and Kiremidjian et al. (1998)[72]	598.50
Bennett et al. (1999)[73]	590.61
Lynch et al. (2001, 2002a, 2002b)[74][75][42]	389.06

These comparisons explain the difference between the other projects conducted in Structural Health Monitoring domain and this system, with respect to the cost of one node of the whole network. According to the comparison above, it is made clear that a node of this system is more cost-effective during production which implies that this system is more cost effective that other general structural health monitoring systems implemented until now.

CHAPTER VI

6.0 Application of Developed Wireless Sensor Network in Target Building

Vibrations in any structures need a proper control due to its nature of causing detrimental effects once it exceeds the allowable limit. Vibrational characteristics such as amplitude of vibration, frequency of vibrations and damping are the three major components of interest as far as engineering applications are concerned. In tall buildings, movements are mainly induced by wind and earthquake. Due to aero-elastic effect, vibrations induced in tall buildings due to wind ,change the wind effects on the buildings [76].

Challenges incorporated in building monitoring compared to bridges was discussed in chapter 3. In this chapter process and steps went through in order to establish the sensor network in the building and the challenges faced is discussed. In addition to the establishment of sensor network the modal damping ratios, peak picking method and filtering methods also have been discussed. Finally, the finite element results have been compared with the operational modal analysis results.

6.1 Damping /System damping

In physics damping is a phenomenon that reduces the amplitude of the vibrations with time. In structural engineering damping plays a pivotal role in controlling the amplitude or displacements of various parts of the structure thus assuring the health of the structure as well as the comfort level of people, use it. Damping of a system is caused due to various mechanisms such as internal frictional forces at the joints, friction of the materials which happens internally, drag effects due to the medium (such as fluid or air) in which the structure is performing, thermos-elastic nature of the material both in micro and macro level, viscous forces in grain boundary, eddy current effects etc.[77][78].However, Damping can be categorized in to major 3 categories known as according to[78] as follows, Viscous damping - Here the damping force is proportional to the velocity of the body. The force is due to the viscosity of the medium in which the motion occurs.

- Structural damping - This is due to the energy dissipated because of the hysteresis action and the energy released at the structural connections.
- Coulomb damping - This is due to the friction in surfaces that are in contact. The force is proportional to the relative displacement between two surfaces.

In addition to above mentioned damping categories, building under goes a significant damping phenomenon known as aerodynamic damping which is caused due to the movement of building in air medium. Aero dynamic damping generally reduces the deflection at the top and the acceleration of the building[76] and need to be considered when wind induced response of tall building is considered [79].

Many buildings are currently studied to find out overall damping as a function of velocity of vibration (Viscous damping). The contribution to the overall damping by the soil structure interaction and the contribution from the intrinsic nature of the material and effect of dampers or vibration absorbers are currently studied by many researchers[79]–[81].

Modal properties are the properties which changes with the modes or the property that changes with the Eigen values. Generally modal masses, modal energies (Kinetic and strain) and modal damping ratios are widely compared and taken into design considerations. Modes need to be matched before any comparisons are done[82].Modal Assurance Criteria (MAC) is used in order to check the agreement between selected modes.

6.2 Experimental modal analysis

In order to identify dynamic characteristic such as natural frequencies, modal damping ratios, mode shapes etc., of a structure, research community widely use methods such as ambient vibration tests, free vibration tests, forced vibration tests, Earthquake response test etc. Out of these methods ambient vibration test is widely used.[83] The modal frequencies of the building resonates with the ambient excitations in ambient vibration test. In forced vibration test, in order get good response signals higher excitation forces are given by external source such as vibrators which has huge mass with eccentricity. Apart from weak signal which is considered to be one and only drawback, ambient vibration tests are well accepted due to the following reasons

- Ambient vibration test is cost effective, because it doesn't need any external excitation force given to the structure which is costly but quantifiable.
- Ambient vibration test creates very low damage to the structure and it falls under one of the reliable non-destructive test methods.
- It is very quick and efficient when there monitoring system has adequate capacity and sensitivity to monitor the acceleration.

Since the signal in ambient vibration test is weak it is not so effective in predicting higher modes.

6.2.1 Sensing response of the structure due to ambient vibrations

The building that was selected to monitor was under construction (construction of non-structural elements) during the period of monitoring. The building didn't have much partitions during the period of monitoring which means the super imposed dead load is lesser in this building, than that of building during operation. In addition to that, the building didn't have filled water tanks and the services were half done. Most of the apartment building are expected to be accommodated by at least 3 people which sums up to 24 people per floor which is the least. However, it could be observed that there are only few people working in the floors during the monitoring period thus reducing the live load of the building.

The construction equipment that were used during construction observed to shake the building floors up to a perceivable level. Equipment such as drillers and vibrators are proven to have capacity to produce noise and vibration that are significant[83]. In ambient vibration tests the building response signal is mainly dependent upon the excitation forces given by the surroundings Structure undergo significant damage as well as notable response when it faces earthquakes and hurricanes. These kinds of responses can readily be captured by normally used accelerometers, because the signal to noise ratio (SNR) is high. However, in ambient vibration tests are dependent on the vibration sources such as movement of imposed loads, Wind loads, Vibration of machineries, traffic loading nearby etc. Response of the structure due to these sources are very small. However, by using accelerometers which as higher resolution this response can be captured. More the accuracy of the accelerometer more would be the potential of the system to detect the response[27].

6.2.2 Details of the building

The target building selected for this case study, is known as Colombo City Centre which is shown in Figure 6.1. This building is a concrete shear wall: moment resisting structure. The building was under construction when the sensors were mounted, introducing challenges to the prediction of the behaviour of the building beforehand. The concrete Skelton of the building had been finished by the time the research was started, but the partitions and finishes were under construction. Because of the stiffness variation of the building with time, in both translational directions, the mathematical model had to be updated accordingly.

The details of the building is listed below

- Height -184.4 m
- Total number of floors - 47 floors + 1 Basement
- Carpark - 656 slots (Total) with double helix ramp.
- Excavation - 13-meter depth
- Foundation type - Combined Pile cap foundation (i.e. A pile raft without transferring load to soil)
- Slabs - Post-tensioned (Totally 450 tonnes) and no beams.

Figure 6.1. Colombo City Centre. (The target building)

6.2.3 Finite element model of the building

As discussed in chapter3 the in order locate the sensors and predict the mode shapes, Finite element model is used and it is very crucial point of SHM. The Finite Element Model (FEM) was done using Etabs which is a commercially available finite element package. The model was updated for the currently experienced loads in order to simulate the real behaviour. According to various codes used in practice, 25% to 30% of the live load is considered along with the dead load when seismic designs are done. However, the mass needs to be adjusted (i.e. contribution is made zero). In addition to this, the super imposed loads such as partition loads and unfilled tanks also were considered when updating and predicting the mode shape. Figure 6.2 shows the modes and natural frequencies obtained from finite element model. The table 4 shows the natural frequencies of five mode shapes. Only first 5 mode shapes were considered due to the mass participation of 70%. Since this is an ambient vibration test, it is not hat advisable to go 70%, because of the low aspect ratio and the higher stiffness of the building. Table 6.2 shows the modal participation ratios of first 5 modes in both X and Y directions.

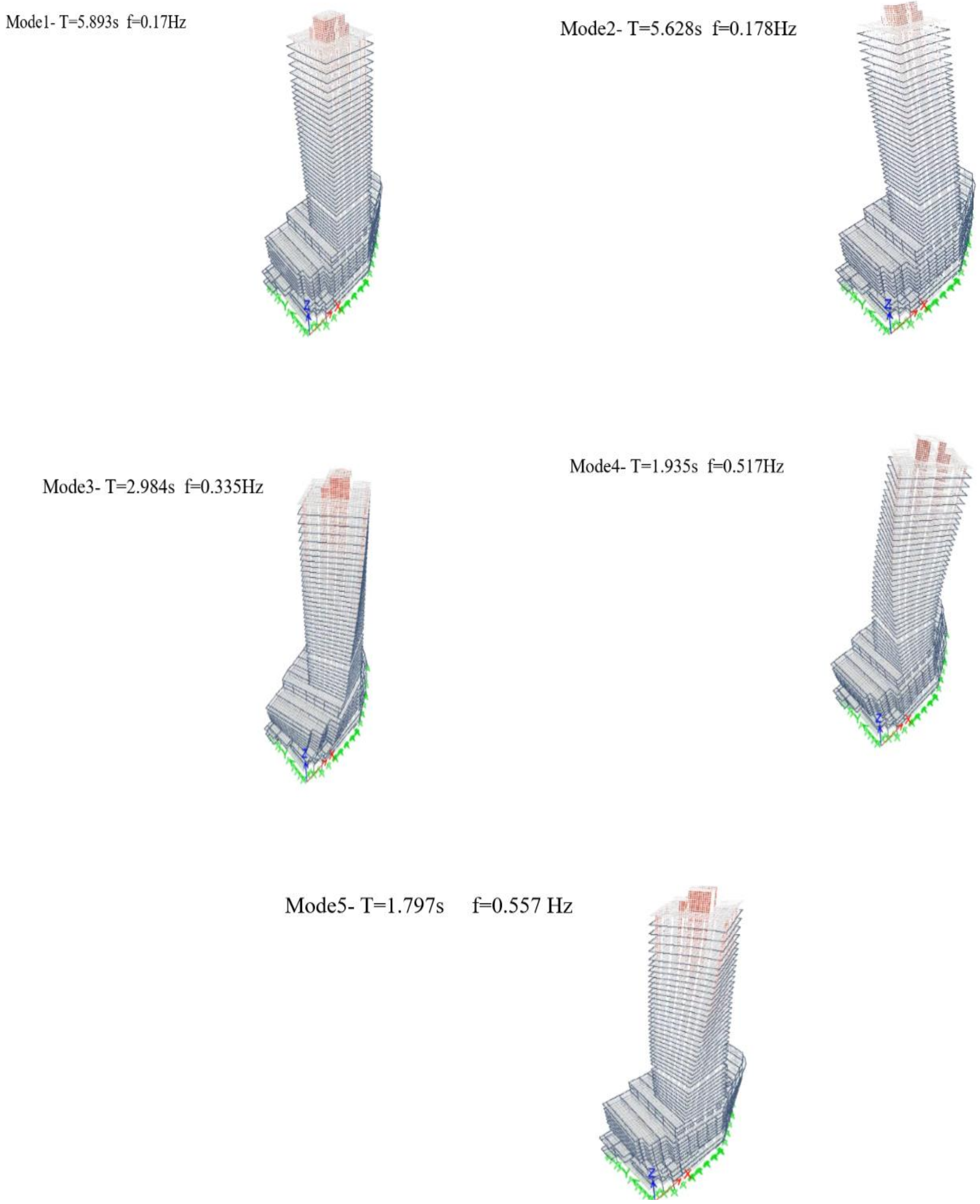


Figure 6.2. Mode shapes and natural frequencies of the building

Table 6.1 Summary of natural frequencies

Mode	Natural frequency (Hz)	Mode shape
Mode1	0.17	Translational
Mode2	0.178	Translational
Mode3	0.335	Torsional
Mode4	0.517	Torsional
Mode5	0.557	Torsional

Table 6.2 Modal participation ratios and sum of first 5 modes in both X and Y directions

Mode	Modal participation factor in X direction	Modal participation factor in Y direction	Sum of Modal participation factor in X direction	Sum of Modal participation factor in Y direction
Mode1	0.416	0.0007	0.416	0.0007
Mode2	0.0011	0.3808	0.417	0.3815
Mode3	0.0322	0.0134	0.4492	0.3948
Mode4	0.2394	0.001	0.6887	0.3959
Mode5	0.0308	0.2692	0.7194	0.4158

6.2.4 Range test before mounting the sensors and locating sensor

Testing and evaluating a network are of utmost importance especially in wireless networks. Wireless network undergoes a variety of challenges that wired networks. Some of these problems are

1) Packet loss due to obstructions in their transmission media such as concrete floors or even metal ducts. Unlike wired networks wireless networks do not have a dedicated

medium for transmission and objects can move through that medium ignorant to the transmission that is happening in the medium. If the wireless transmission wave does not have the penetration power or the ability to somehow reach the destination.

2) Addition of too much noise due to the anomalies in the transmission medium: As wireless transmission does not have a dedicated medium; the transmission medium can be subjected to various changes which can add noise to the data packet.

Although various tests should be conducted in a wireless network, due to the above reasons, the most important one becomes the range test between nodes. [84] Range testing implies testing the distance that can be covered when transmitting data from one node to the other at the geographical location at which the system is implemented. The details of the range test that was done on our system with 14dbm transmitters are given below through Table 6.3.

Table 6.2. Range test done in open air with our system

Data rate	For 14 dbm Tx (Antenna)	Distance
300 kb/s	-117 dB	800m
300 kb/s	-126 dB	1500m
300 kb/s	-136 dB	1800m
300 kb/s	-153 dB	2000m

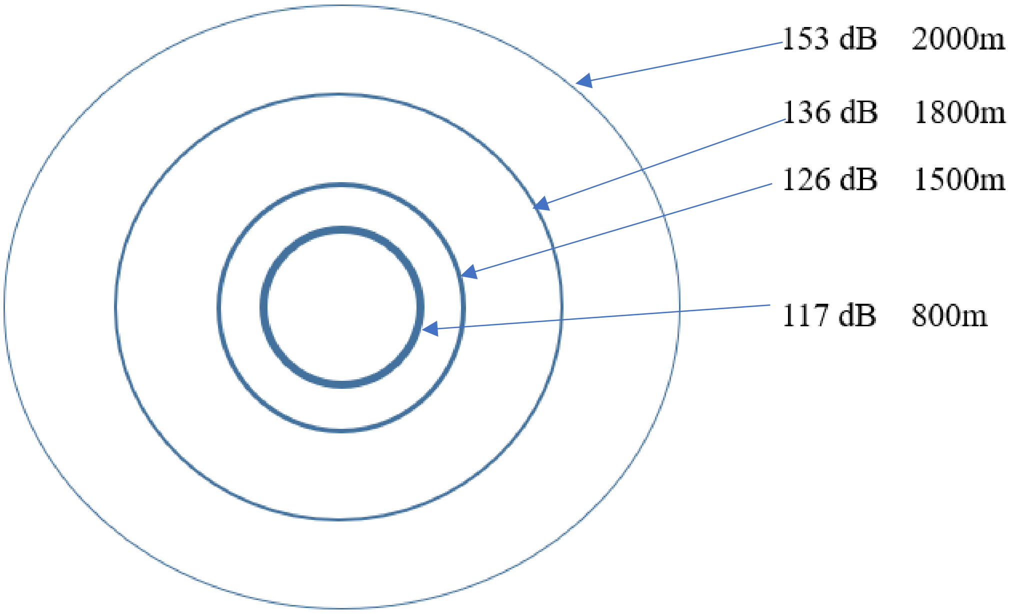


Figure 6.3. Range test done in the open air with RF transmission

After the range test the sensors were mounted in sequential manner as shown in Figure 6.3 above. Since the wireless sensor network that is established consists only 5 nodes and the number of floors decided to monitor is 26 the sequential method is chosen. Here 7 floors are covered at once and then keeping one node as common rest of the four nodes will be taken upwards. In Figure 27 below this process is explained for 4 nodes. And the Figure 6.4 shows the locations of sensors in the real building.

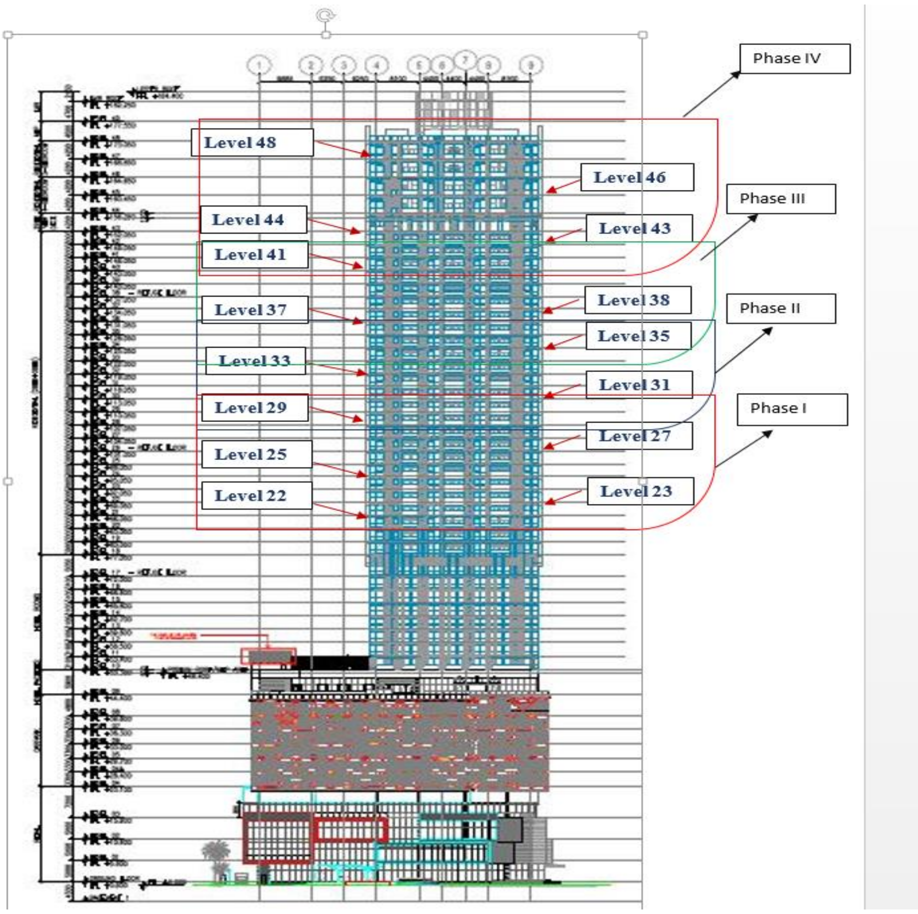


Figure 6.4. Sensor Locations

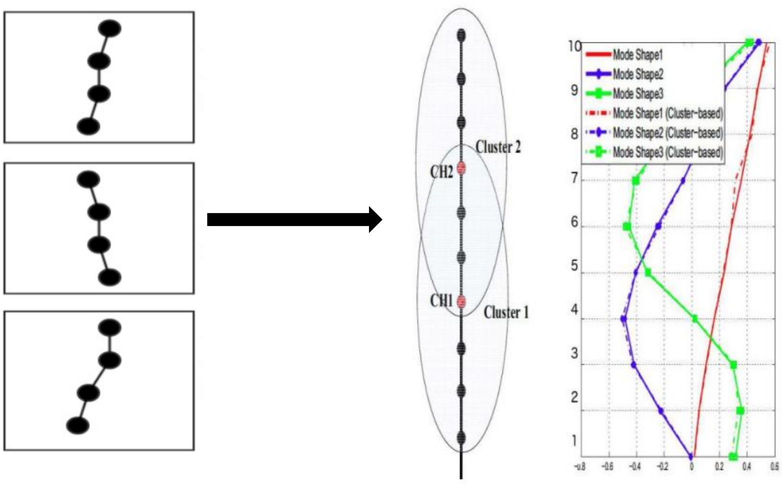


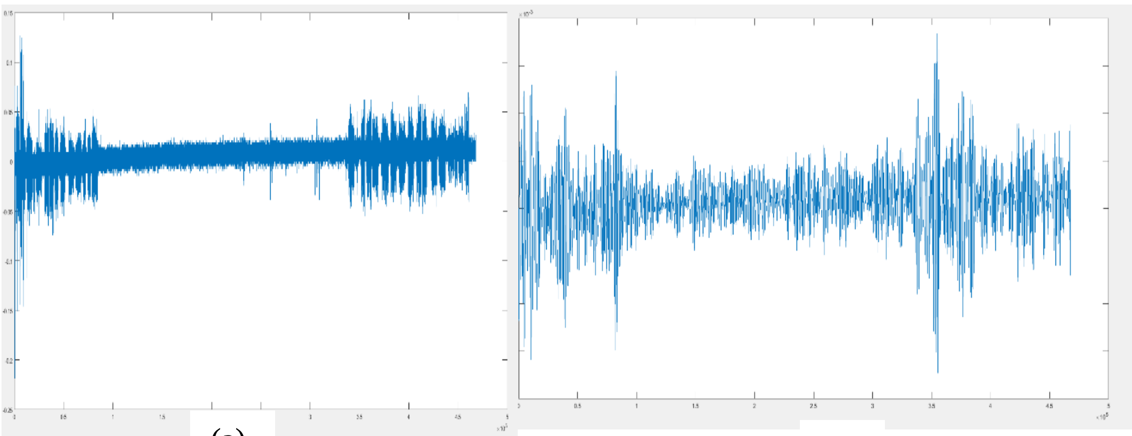
Figure 6.5. Depiction of establishing sensors in sequential manner

6.2.5 Fourier transform and peak picking method

Fourier transform is an efficient tool that converts time response in to frequency response using equation 6.1. This will give the overall idea about the modal deflection and phase angle

$$FT(\acute{\omega}) = \int_{-\infty}^{\infty} x(t)e^{-j\acute{\omega}t}dt \qquad (6.1)$$

The sensors were located as mentioned in 6.2.2- and 24-hours data was collected continuously. Figure 6.6 (a) shows the time history of 24-hour data of one node. This time history of data is then converted in to frequency domain using fast Fourier transform as shown in Figure 6.7 Since the building natural frequency is lying in-between 0.1 Hz to 0.6 Hz low pass and high pass filters are applied at 1Hz and 0.08 Hz respectively. Low pass filter and high pass filter are nothing but a method that cut off the frequencies except for the specified range. Figure 6.6 (b) shows the response after filtering using low pass and high pass filters. Sample representative data is attached in Annex B.



(a) (b)

Figure 6.6. (a) Sample time history data of 48th floor for 24 hours (b) Sample time history data after filtering

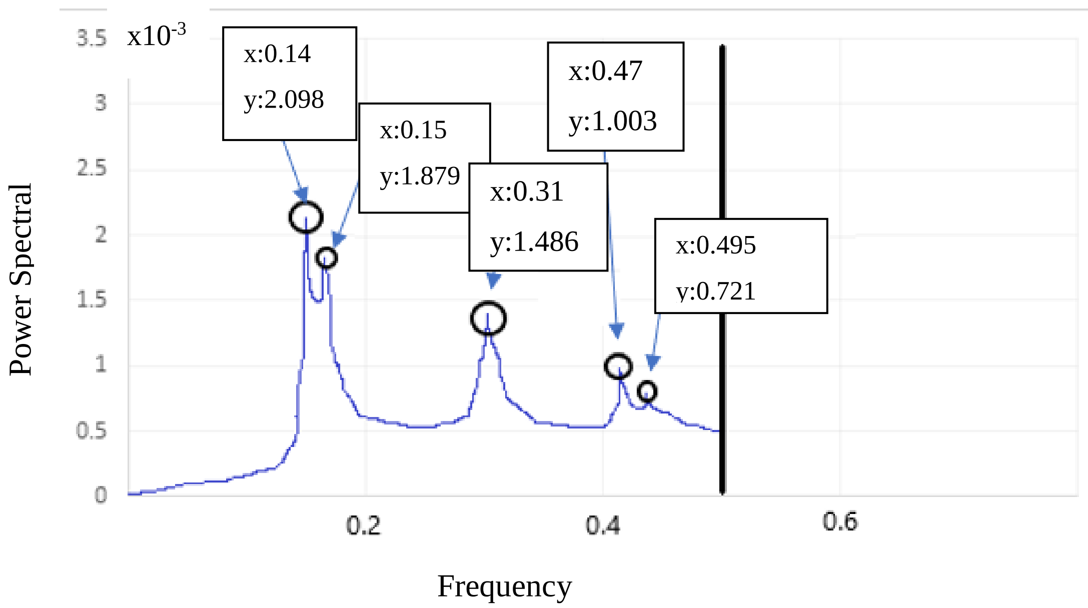


Figure 6.7. Fast Fourier data analysis of the data shown in Figure 3.1 (a).

Table 6.3 Summary of Natural frequencies and comparison between FEM and OMA values

Mode	Period	Frequency (FEM)	Frequency (OMA)
Mode1	5.893	0.17	0.14
Mode2	5.628	0.178	0.15
Mode3	2.984	0.335	0.31
Mode4	1.935	.517	0.47
Mode5	1.797	0.557	0.495

6.3 Modal damping ratios and mode shapes

Modal damping ratio is calculated using $1/\sqrt{2}$ method. Using modal data extracted from all 6 nodes damping ratio is averaged and summarised in Table 6.5. However, it has to be noted that damping ratios increases with amplitude. Calculation of modal damping ratio of mode1 at the node which was established at the topmost point (48th floor) is shown below in Figure 6.8.

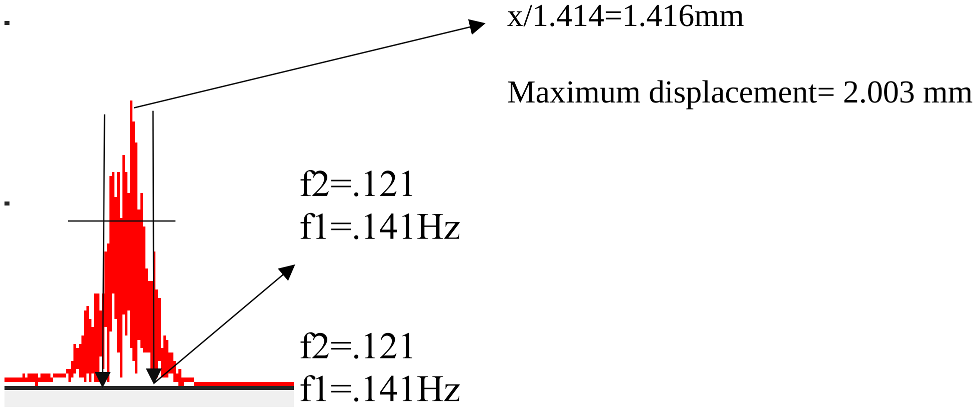


Figure 6.8. Calculation of modal damping ratio

Table 6.4 Modal damping ratios with natural frequencies

Mode	Natural Frequency using OMA	Damping ratio
Mode1	0.14	1.57 %
Mode2	0.15	1.63%
Mode3	0.31	1.69%
Mode4	0.47	1.7%
Mode5	0.495	1.85 %

6.4 Modal Assurance Criteria (MAC)

Modal assurance criteria is used to statistically indicate differences in mode shapes. This is sensitive to large differences but insensitive to small differences in mode shapes. It can be used to compare the measured modal vector of the structure with the modal vector that is determined using analytical model. It can also be used for the comparison of modal vectors that are obtained from two different modal identification process.[82][85][86]

$$MAC(r,q)=\frac{\left|\{\varphi_A\}_r^T\{\varphi_X\}_q\right|^2}{\left(\{\varphi_A\}_r^T\{\varphi_A\}_r\right)\left(\{\varphi_X\}_q^T\{\varphi_X\}_q\right)}, \tag{6.2}$$

Nomenclature

$\{\varphi_X\}_q$ test modal vector, mode q

$\{\varphi_A\}_r$ compatible analytical modal vector, mode r

$\{\varphi_X\}_q^T$ transpose of $\{\varphi_X\}_q$

$\{\varphi_A\}_r^T$ transpose of $\{\varphi_A\}_r$

Modal assurance criteria (MAC) takes value from 0 to 1, where 0 represents no consistent correspondence and 1 represents a good correspondence. Values larger than 0.9 indicates a satisfactory level of correspondence.

Ideally the MAC matrices are not identity matrices because the modes are mass orthogonal not directly orthogonal. The reason is, work done by particular mode through other mode is zero. Most important fact is, MAC can only measure the consistency. In order to measure validity, the method that is relied upon has to be accurate enough and there are certain other.

Calculations and Interpretation of MAC values calculated

The reasons for MAC values closer to 0.

- If the system is dynamic or the properties that influence the modal properties such as mass and stiffness, change with time significantly.
- If the system is not linear.
- Error in the method of extracting the modal response of the structure.

Figure 6.9 shows the way of typical representation of MAC and Figure 6.10 shows typical rough mode shapes of first 3 mode shapes

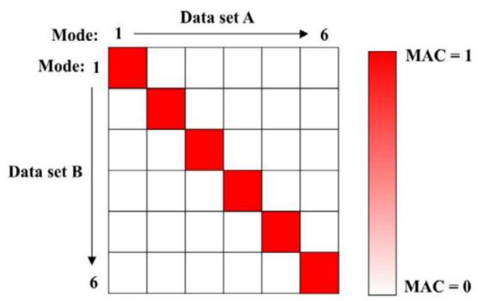


Figure 6.9 – MAC representation .Source [85]

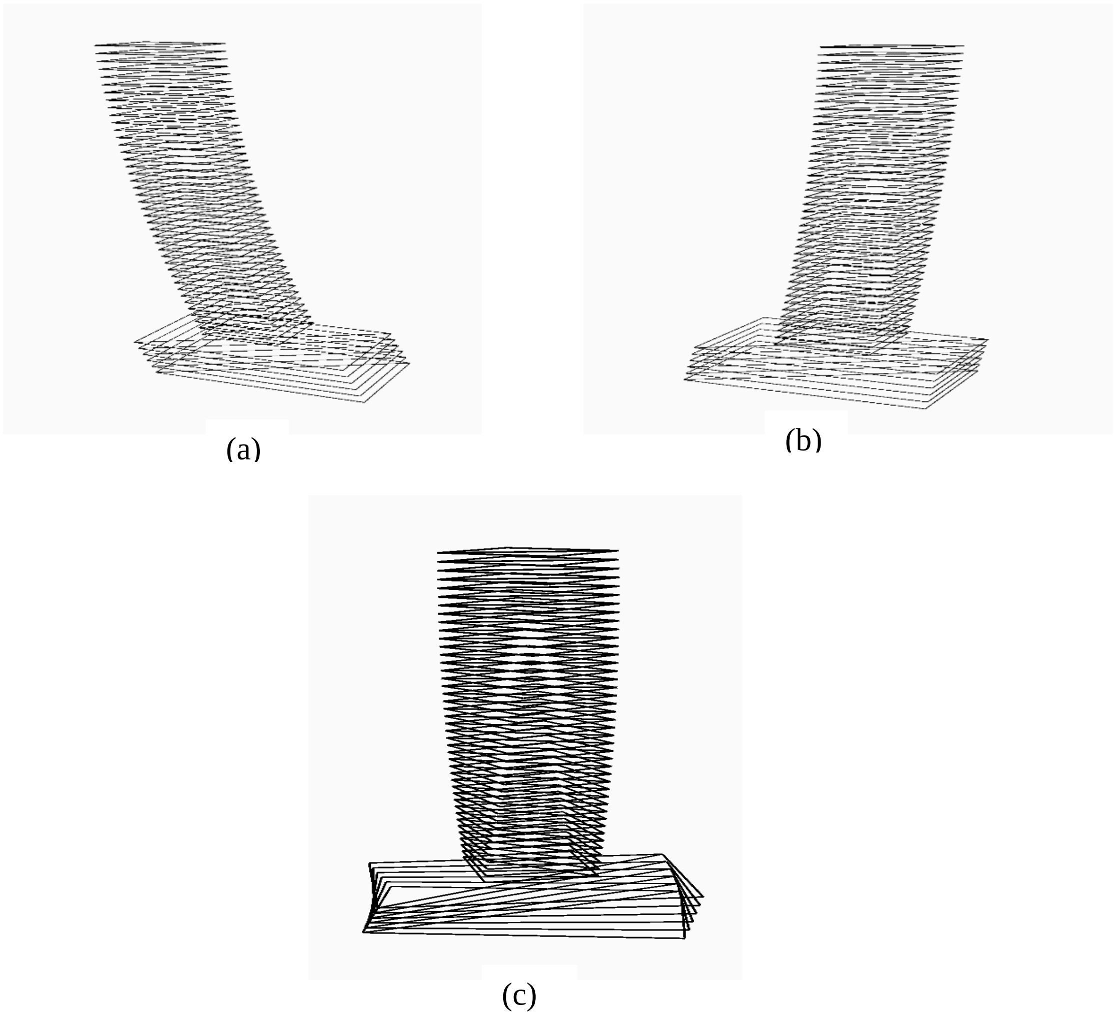


Figure 6.10 (a) Mode1 (b) Mode2 (c) Mode3

All the mode shapes were fed in to the equation for MAC and it is plotted as below in Figure 6.11. It can be seen except for mode number 5 all other modes show a good co relation (.86 – 0.9) with the FEM prediction.

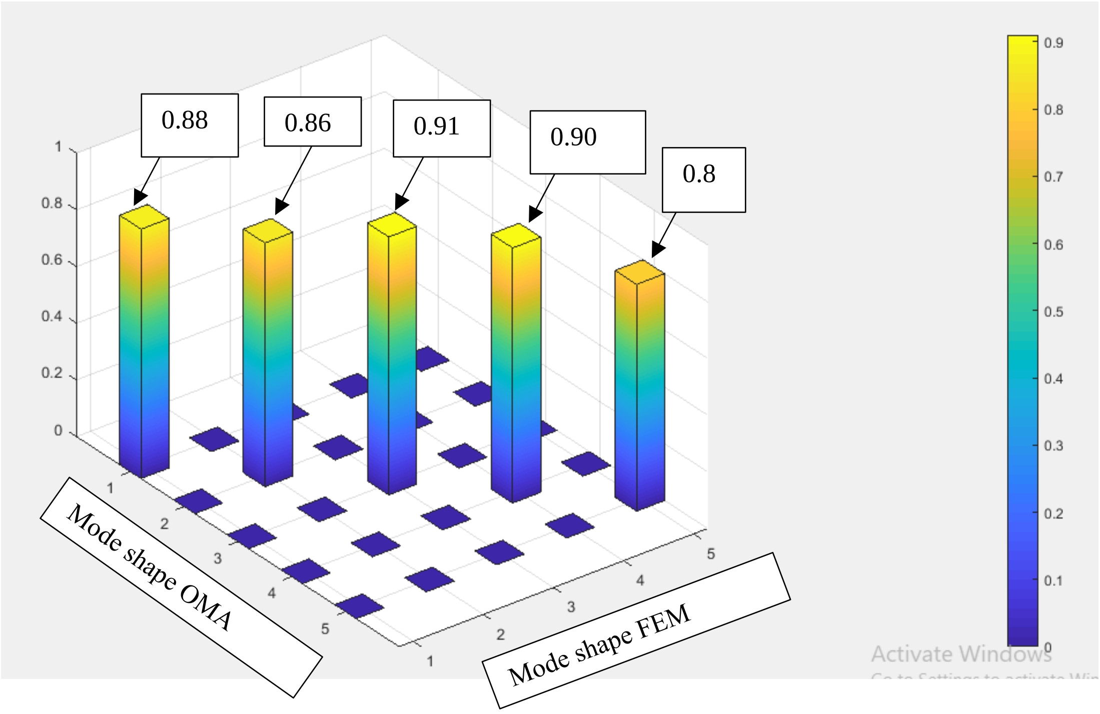


Figure 6.11 MAC Values (Correlation) of the case study

CHAPTER VII

7.0 Conclusions and Recommendations

7.1 Discussion and conclusions

This research is first of all an attempt to establish proper structural health monitoring in Sri Lanka. Since our country falls under the category of developing country the resources being spent on structures including SHM need to be handled very efficiently. After doing a comprehensive literature review and consulting peer professionals, Introducing WSN to Sri Lankan and establishing a proper ground for Structural health monitoring was thought to be a best option. This will not only save our structures and also will pave the way for safe and cost-efficient design in future.

In this thesis establishing a wireless sensor network and online data logging system is discussed and it was proven to be work efficiently. The inherent challenges that are related to wireless sensor networks such as time synchronization is successfully achieved with low cost involved. Using the data that was collected using the established system the modal parameters of a target building was extracted and this part of monitoring accelerations of building will pave the way for many future applications such as human comfort monitoring, damage prognosis and movement in large flexible structures.

After this research it was possible to arrive at 5 main conclusions

1. It is worth spending a significant amount of money for the sensor compared to the overall cost of the sensor node, because sensor is the part which initiates the process of monitoring building response. A significant amount of work such as reviews, comparisons of past similar projects, calibration has to be done in order extract absolute value from accelerometer. In this research selecting and calibration of a selected accelerometer were successfully done.
2. The architecture of the hardware of the sensor node is very important and need to be optimized. All three platforms (Sensor board, Processor board and radio frequency board) that contribute for the final sensor

node have to be optimized to achieve low cost and low power consuming sensor node. Selecting suitable Operating System (OS), proper wireless communication technology and telecommunication protocol are equally important in order to increase the efficiency.

3. Making accurate mathematical model that simulates real mass and site conditions (such as filled tanks, rotating machines, construction equipment) is important to locate the sensors at proper locations to capture the response of the building efficiently. This is crucial in order to compare the results with operational mode shape with that of simulated mode shape.
4. When mounting the sensors several checks need to be done. A proper range test must be done in the real structure in order to ensure that the distance at which the sensors are mounted won't be a problem for establishing wireless communication. The other interactions like iron ducts, other interrupting frequencies needed to be avoided to increase the range.
5. For building monitoring, the hopping method of meshing is the only possible way of establishing the wireless sensor network because of through slab data transferring.
6. Modal parameters such as natural frequencies and modal damping ratios can be extracted accurately due to the mass participation ratio is higher for lower modes. However, in order to sense the modal parameters of high frequencies, the accuracy of the accelerometer and the Signal to noise ratio need to be higher.
7. Using only 6 nodes response of target building Colombo City Centre was monitored and the first 5 mode shapes tallied with the mode shapes calculated using finite element model. (i.e. MAC values are close to 0.9).

7.2 Limitations and future studies

1. In this system developed, the entire data including noise (sensed at high frequency) is sent to the cloud or webserver. This is done as this data can be used for comfort monitoring as well, that is why the data is sent to the cloud directly irrespective of the amount of data. However, this is not efficient when Sub-1 GHz is used. When it comes to data sharing using radio waves, the data transferred need to be small enough so that it can be sent in real time. If the data is processed at the node level and only the modal data is sent through packet, then the data that need to be transferred is very small and real time monitoring is possible.
2. The synchronization method used here is error method where the error is sent with the packet in order to achieve synchronization. However, there is another method which is known as error plus skew method where the error or the drift of the clock is monitored by the node itself and the synchronization lost is addressed locally. This method is suggested for future wireless sensor networks.
3. The synchronization method explained here is subjected to progressive error where the error is multiplied by the number of hops. However, this error in synchronization can be kept same for each hoping thus the scalability of the system can be increased.
4. The transmission protocol used here is GSM module even though the other protocols such as NB-IoT and LoRaWAN technologies are discussed. In future, the range can be increased using NB-IoT.
5. The sensor node that is developed is mainly using commercially available off the shelf products. However, by doing further optimization, unnecessary part of these off the shelf products can be eliminated and very productive PCB design can be made which might not show huge cost saving for lesser number of nodes, but it will definitely show huge cost saving when number of production is high.

6. The sensor node is having a battery which can survive 2 hours when there is no power. However, with the introduction of further self-charging sustainable methods the battery life can further be increased to days or even months, without external power supply.
7. The modal parameters are monitored and saved only for couple of days under this research due to the time limitations. However, with the introduction of dense arrays of sensor nodes along with long term monitoring further meaningful results such as global stiffness variation with time.

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APPENDICES

APPENDIX A

Laboratory Synchronization data

Session number	Sample Number																				Average	Std Dev
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**		
1	44	52	56	36	58	76	36	48	54	42	48	24	40	62	80	66	46	62	40	46	50.8	13.83
2	12	56	62	50	68	50	62	40	54	40	56	32	46	70	44	36	18	54	16	56	46.1	16.61
3	90	14	50	32	82	64	74	92	36	56	68	86	34	78	66	40	92	48	92	40	61.7	23.98
4	46	60	18	92	30	84	60	2	76	92	46	88	34	48	92	48	84	32	46	60	56.9	26.59
5	80	32	74	58	70	86	26	12	82	66	76	34	34	50	32	76	54	70	84	68	58.2	22.48
6	63	29	35	14	31	52	36	54	24	65	19	15	27	66	66	50	27	12	44	59	39.4	18.75

7	53	62	35	50	61	21	25	21	31	10	51	43	34	63	27	13	37	55	39	55	39.3	16.53
8	28	38	50	64	57	64	58	37	34	28	43	48	12	13	21	20	59	46	52	36	40.4	16.39
9	54	69	24	18	10	47	59	41	17	19	54	46	32	33	20	16	60	55	34	37	37.25	17.62
10	43	32	39	43	14	23	28	32	68	46	10	32	69	36	58	30	49	68	42	22	39.2	17.02
11	51	24	20	16	23	15	59	25	10	63	37	26	23	57	62	30	19	19	28	52	32.95	17.51
12	15	38	30	45	37	34	49	63	12	54	27	62	41	62	70	54	46	50	19	16	41.2	17.39
13	24	52	27	53	28	29	58	57	16	22	17	62	40	53	43	44	18	53	30	40	38.3	15.25
14	38	69	29	26	57	70	52	62	28	24	35	60	27	49	27	38	31	19	62	59	43.1	16.86
15	60	68	62	33	41	61	58	41	20	51	38	20	41	16	43	21	46	17	41	13	39.55	17.24
16	65	56	61	56	12	43	10	65	51	58	27	50	65	37	27	11	35	18	67	68	44.1	20.44
17	49	48	42	59	25	33	50	41	19	67	12	62	54	19	59	40	27	63	36	12	40.85	17.48
18	26	55	29	23	32	31	45	44	18	38	68	67	31	32	66	25	18	13	38	66	38.25	17.62
19	17	25	36	69	67	14	70	41	64	39	27	34	59	68	46	21	33	67	56	27	44	19.36
20	51	17	63	22	24	44	68	67	68	45	39	27	51	39	24	64	52	46	64	67	47.1	17.32

21	25	16	61	53	49	43	56	36	30	68	57	35	46	68	13	10	13	13	22	20	36.7	19.71
22	69	41	19	66	35	22	28	54	32	22	60	24	12	19	35	47	28	53	10	69	37.25	19.05
23	20	45	56	62	57	56	24	54	23	58	59	56	44	65	60	69	29	48	48	31	48.2	14.97
24	42	12	63	28	29	31	11	60	25	67	18	56	63	55	47	60	38	56	24	10	39.75	19.49
25	18	62	24	44	50	53	28	57	29	62	21	16	53	21	59	64	25	35	29	51	40.05	16.93

APPENDIX B

Sample of the data generated from our system

(from 29th of June 2019 20:30:22 to 29th of June 2019 20:30:40)

29.06.2019 20:30:22	0,	-9.754914551,	0.318537598
29.06.2019 20:30:22	-0.00239502,	-9.75970459,	0.328117676
29.06.2019 20:30:22	-0.00239502,	-9.75970459,	0.328117676
29.06.2019 20:30:22	-0.00239502,	-9.75970459,	0.328117676
29.06.2019 20:30:22	-0.00239502,	-9.75970459,	0.328117676
29.06.2019 20:30:22	0.00239502,	-9.75730957,	0.323327637
29.06.2019 20:30:22	0.00239502,	-9.75730957,	0.323327637
29.06.2019 20:30:22	0.00239502,	-9.75730957,	0.323327637
29.06.2019 20:30:22	0.00239502,	-9.754914551,	0.328117676
29.06.2019 20:30:22	-0.00239502,	-9.754914551,	0.328117676
29.06.2019 20:30:22	-0.00239502,	-9.754914551,	0.328117676
29.06.2019 20:30:22	-0.00239502,	-9.754914551,	0.328117676
29.06.2019 20:30:22	0.043110352,	-9.752519531,	0.277822266
29.06.2019 20:30:22	0.043110352,	-9.752519531,	0.277822266
29.06.2019 20:30:23	0.043110352,	-9.752519531,	0.277822266
29.06.2019 20:30:23	0.043110352,	-9.752519531,	0.277822266
29.06.2019 20:30:23	0.009580078,	-9.747729492,	0.35685791
29.06.2019 20:30:23	0.009580078,	-9.747729492,	0.35685791
29.06.2019 20:30:23	0.009580078,	-9.747729492,	0.35685791
29.06.2019 20:30:23	0.009580078,	-9.747729492,	0.35685791
29.06.2019 20:30:23	-0.023950195,	-9.762099609,	0.313747559

29.06.2019 20:30:23	-0.023950195,	-9.762099609,	0.313747559
29.06.2019 20:30:23	-0.023950195,	-9.762099609,	0.313747559
29.06.2019 20:30:23	-0.004790039,	-9.754914551,	0.328117676
29.06.2019 20:30:23	-0.004790039,	-9.754914551,	0.328117676
29.06.2019 20:30:23	-0.004790039,	-9.754914551,	0.328117676
29.06.2019 20:30:23	-0.004790039,	-9.754914551,	0.328117676
29.06.2019 20:30:23	-0.00239502,	-9.75730957,	0.316142578
29.06.2019 20:30:24	-0.00239502,	-9.75730957,	0.316142578
29.06.2019 20:30:24	-0.00239502,	-9.75730957,	0.316142578
29.06.2019 20:30:24	-0.00239502,	-9.75730957,	0.316142578
29.06.2019 20:30:24	0,	-9.752519531,	0.313747559
29.06.2019 20:30:24	0,	-9.752519531,	0.313747559
29.06.2019 20:30:24	0,	-9.752519531,	0.313747559
29.06.2019 20:30:24	0,	-9.752519531,	0.313747559
29.06.2019 20:30:24	0,	-9.752519531,	0.320932617
29.06.2019 20:30:24	0,	-9.752519531,	0.320932617
29.06.2019 20:30:24	0,	-9.752519531,	0.320932617
29.06.2019 20:30:24	-0.004790039,	-9.752519531,	0.313747559
29.06.2019 20:30:24	-0.004790039,	-9.752519531,	0.313747559
29.06.2019 20:30:24	-0.004790039,	-9.752519531,	0.313747559
29.06.2019 20:30:24	-0.004790039,	-9.752519531,	0.313747559
29.06.2019 20:30:25	0.007185059,	-9.752519531,	0.320932617
29.06.2019 20:30:25	0.007185059,	-9.752519531,	0.320932617
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29.06.2019 20:30:40   -0.011975098, -9.754914551, 0.313747559

APPENDIX C

Matlab code of data extraction and modal parameter extraction

```
%% mikexcohen.com

%% band-pass filtering
clear variables
clear all
clc
load Buildingdata.txt
figure(1), clf
subplot(111)
datain=Buildingdata(1:468000,5);
plot(datain)
% specify Nyquist freuqency

nyquist = 130/2;

% filter frequency band
filtbound = [0.1 .13]; % Hz

% transition width
trans_width = 0.2; % fraction of 1, thus 20%

% filter order
filt_order = round(3*(100/filtbound(1)));

% frequency vector (as fraction of Nyquist
ffrequencies  = [ 0 (1-trans_width)*filtbound(1) filtbound
(1+trans_width)*filtbound(2) nyquist ]/nyquist;

% shape of filter (must be the same number of elements as frequency
vector
idealresponse = [ 0 0 1 1 0 0 ];

% get filter weights
filterweights = firls(filt_order,ffrequencies,idealresponse);

% plot for visual inspection
figure(2), clf
subplot(211)
plot(ffrequencies*nyquist,idealresponse,'k--o','markerface','m')
set(gca,'ylim',[-.1 1.1],'xlim',[-2 nyquist+2])
xlabel('Frequencies (Hz)'), ylabel('Response amplitude')

subplot(212)
plot((0:filt_order)*(1000/65),filterweights)
xlabel('Time (ms)'), ylabel('Amplitude')

% apply filter to data
```

```
    filtered_data =
filtfilt(filterweights,1,double(Buildingdata(1:468000,5)));


figure(3), clf
plot(filtered_data)
hold on
```

```
% compare three transition widths

nyquist     = 130/2;
filtbond    = [ .1 .13 ];
t_widths    = [.1 .15 .2];
filt_order = round(3*(100/filtbond(1)));

idealresponse = [ 0 0 1 1 0 0 ];

ffrequencies  = zeros(3,6);
filterweights = zeros(3,filt_order+1);

% frequency vector (as fraction of Nyquist)
for i=1:3
    ffrequencies(i,:)  = [ 0 (1-t_widths(i))*filtbond(1) filtbond
(1+t_widths(i))*filtbond(2) nyquist ]/nyquist;
    filterweights(i,:) =
firls(filt_order,ffrequencies(i,:),idealresponse);
end

% plot
figure(4), clf
subplot(211)
plot((1:filt_order+1)*(1000/65),filterweights')
xlabel('time (ms)')
title('Time-domain filter kernel')

filterFreqDomain = abs(fft(filterweights,[],2));
frequenciesHz     = linspace(0,nyquist,floor(filt_order/2)+1);
subplot(212)
plot(frequenciesHz,filterFreqDomain(:,1:length(frequenciesHz)))
set(gca,'xlim',[0 60],'ylim',[-.1 1.2])
xlabel('Frequencies (Hz)')
title('Frequency-domain filter kernel')
legend({'filter 10%','filter 15%','filter 20%'})

figure(4), clf
```

```
hold on
Fs=130;
Ts=1/Fs;
dt=0:Ts:3600-Ts;



FourierTrans=fft(filtered_data);
FourierTransabs=abs(FourierTrans);
Phase=angle(FourierTrans);
length(Phase);
subplot(3,1,1)
plot((FourierTransabs/(130)),'g');

nfft=length(filtered_data);
% nfft2=2.^nextpow2(nfft);
fy=fft(filtered_data);
fy=fy(1:nfft/2);
xfft=Fs*(0:nfft/2-1)/nfft;
subplot(3,1,2)
y=abs(fy)*(1/Fs)*.01;
plot(xfft,(y),'b');
subplot(3,1,3)
plot(Phase,'b');


% MAC values%


Z = [ 0.88 0 0 0 0  ;0 0.86 0 0 0 ;0 0 .91 0 0 ;0 0 0 .90 0 ; 0 0 0
0  .8;];
b = bar3(Z,.4);
colorbar
for k = 1:length(b)
    zdata = b(k).ZData;
    b(k).CData = zdata;
    b(k).FaceColor = 'interp';
end
```