


**TECHNO ECONOMIC ANALYSIS, DESIGN AND  
IMPLEMENT A SUITABLE COMMUNICATION  
METHOD FOR UTILITY SYSTEMS**

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## Abstract

This thesis presents a research work which is carried out to optimize the Zigbee based remote meter reading network. There are various technologies available to automate the meter reading such as PLC, GSM, Optical fibre and RF technologies. As far as utilities providers are concerned, their focus is on a reliable RMR system to read the meter at minimum possible cost. The development of a reliable RMR system is highly dependent on telecommunication infrastructure which is costly if GPRS is used as a way of communication. Therefore, research were done in depth to analyse the cost and function of RMR system as large number of sensors are used in the electrical utility.

This particular research is on data concentrator based RMR system focusing on the analysing of communication delay and resource optimization.

In this research Matlab Simulink software was used for simulations and Visual Studio C# is used for creating the software. Several simulations were carried out in this research, for simulating communication speed, communication path and study the behaviour with the presence of noises.

As the final outcome of the research, software was developed for selecting Zigbee power rating based on GPS locations and generated algorithms for calculating communication delay and path which can be incorporated to the coordinator.



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## List of Abbreviations

Abbreviation	Description
RMR	Remote Meter Reading
RF	Radio Frequency
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
PLC	Power Line Carrier
AMR	Automatic Meter Reading
SIM	Subscriber Identity Module
IOT	Internet of Things
RSSI	Received Signal Strength Indicator
ZTR	ZigBee Tree Routing
STR	Shortcut Tree Routing
AODV	Ad Hoc On Demand Distance Vector
DSDV	Destination Sequenced Distance Vector
TOD	Time Of Day
OBIS	Object Identification System
EDIS	Energy Data Identification System
LQI	Line Quality Index
LED	Light Emitting Diode
LD	Laser Diode



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### 1. INTRODUCTION

#### 1.1. Introduction to Remote Meter Reading Technology

There are many communication mediums like GPRS, GSM, RF, PLC, RS485, RS232, Ethernet etc used to link remote nodes within the electrical sector. The communication medium selection criteria are varying according to the indoor or outdoor communication, node to node distance, and available communication mediums etc. And massive numbers of remote nodes are available for linking with central server in electrical utility sector.

In indoor communication like within a substation, mainly Ethernet, RS 485, RF, PLC etc are used as communication mediums. In most of the cases wired communication mediums are used than wireless communication mediums. Because of the unreliability of wireless communication and the reliability of wired communication mediums. In addition to that wire laying between nodes is possible in indoor systems.



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In outdoor systems like electricity distribution system, transmission system etc, mainly PLC, RF, GPRS etc are used as communication mediums. But massive numbers of nodes are available to interface as remote nodes to the central server. LBS, Energy Meters, System Status Monitoring Equipment, etc are going to be interfaced to the central server. Those nodes can be categorized according to the criticalness of the communication operations. The communication requirement for the LBS can be categorized in to the critical operation with reading and writing. But in meter reading and system monitoring equipment can be categorized in to non-critical and read only remote nodes with small number of writing operations. Thus direct communication link is required for the LBS operations and non-direct communication links can be used for meter and system status monitoring equipment. In the research communications links related to remote meter reading (RMR) is considered because of the massive number of nodes.

In the RMR communication links are established between central server and energy meters. The number of communication links will be increased when a new electricity customer is joined. As an energy meter server, it is required to connect every meter nodes in a fixed time interval like 15 min or 1 hour for maintaining the load profiles. In this situation, server trying to establish connection between server and the meter ends for polling data. In this case communication service providing company has to manage the data traffic and at the peak time also. Thus it will increase the probability of failure to establish the link. This is getting worse while retrying to establish the link within the link fail situations. This leads repeating the data for initializing the link, sending same data and transmitting acknowledgment data. This will cause an unnecessary data burden over data transfer.

Now a days RMR is developed up to the Automatic Meter Reading (AMR). In AMR meter readings are collecting with the initiation of meter end and the server end. Some systems used concentrator based systems rather than direct connection to the meter. In concentrator based systems, meter readings are collected from small meter groups to the concentrator like small server and push all data to central server. For data collecting within the small groups, some low operating cost communication mediums can be used. PLC, RF like Zigbee, Optical fiber etc can be used for communication within the small groups.

## **1.2. Analysis of Remote Meter Reading Technology**

In the early stages of electricity energy measurement, most popular energy meter type was electromechanical energy meter. Its concept is based on a magnetic field which is proportional to the current and voltage. There was not any communication interfaces. With the development of energy meter, Static Energy Meter and Electronic Energy Meter came to the field with communication facility. In addition to that prepaid concept is being also entering to the field with the time being. So many parameters like voltage, current, active power, reactive power, apparent power, load profile, fault log etc can be collected from modern energy meters with high accuracy. In addition to that, communication facility is also available in most of the modern energy meters. Communication mediums like GPRS, PLC etc are used with those type meters. Some energy meters have inbuilt GPRS communication module.



Those type meters are occupied with a SIM (Subscriber Identity Module) which has unique identification number, wireless communication transmitter, receiver and data storage unit in addition to data measurement sensors and electronics.

Now a day the most popular and easiest method is using a GPRS modem for communication. In that scenario, electricity utility has to incorporate with telecommunication service providers such as Mobitel, Dialog, Airtel etc. But the issue is the telecommunication providers do not provide suitable packages to meter reading with every consumer, every transformer, and other major points in the distribution system which is included communication ends. Also the bandwidth of the data connection and switch on duration of the mobile connection is decided by the telecommunication service provider. Finally, the cost of the data package is calculated by the energy meter readout cost with monthly rental. So electricity utility has to pay massive amount to the telecommunication provider. Sometimes it could reduce the net profit by the monthly electricity bills.

So as a solution for that, concentrator or coordinator based systems are used in energy meter sector. System concentrator can collect data from all the related meter nodes and send data bundle to the server. Wireless or wired communication mediums like Zigbee, Bluetooth, Wifi, PLC, Optical Fiber etc can be used for that. But it's a new technology for the RMR sector.

### **1.3. Problem Identification**

In RMR and AMR there should be a communication link between meter end and the server. Energy meters generates several types of data like kWh reading, readout data set, fault or other indications in faulty situations or in a exceeding limits as per the settings in the meter, logs etc. In addition to that electricity utility hopes to collect massive number of data with high frequency. But in direct communication like GPRS, the communication data quantity will be limit according to the resources of communication service provider. Anyway electricity utility has to utilize lager portion of mobile communication resources from communication provider. It is like a maintaining a separate communication infrastructure for electricity utility when considering huge number of energy meter network. In LECO, there are around 5 lack

electricity consumers while CEB having 5 million consumers. So cost of communication is nearly equal to the cost of telecommunication infrastructure and its maintenance cost. Like that way it's better to maintain a telecommunication infrastructure by an electricity utility. But it's not a solution for that. In addition to that, it takes approximately 2 minutes to read a single meter and when considering the five lacks consumers it is unfeasible to read data in time from meters. By considering all above issues, coordinator or concentrator based energy meter reading is feasible than direct connected meter reading.

In coordinator based meter reading can be based on RF technology like Zigbee, Wifi, Bluetooth etc, PLC etc with a mobile communication. In that scenario, one mobile link is utilized by many number of energy meters. So it can be reduced utilization of telecommunication infrastructure. But if the coordinator based meter network is used as separate link to the each meter within the group, it will increase the total meter reading time. In another way, if coordinator collects all the data within the group and send collected data to server, then total reading time will be reduced.

In LECO, a Zigbee network was installed for creating coordinator based energy meter network. There are two types of Zigbee module available commercially.

- ❖ Zigbee Pro 63 mW
- ❖ Zigbee 1 mW

But Zigbee 63 mW modules were used for installation. Zigbee is used mesh network for communication. There was no proper study carried out when using zigbee as electricity energy meter networks. So better optimized reading time can be achieved and other network resources can be optimized by those type study.

In addition to that upcoming requirements of electricity utility like demand response, IOT (Internet of Things) platforms etc can be achieved by those type networks. In demand response, there should be a communication link to home appliances with high electricity demand for controlling. Those type networks will be helpful to prevent total blackouts.

#### **1.4. Objective**

The study was carried out for optimizing the Zigbee network in economical wise, performance wise and reliability wise. So main objectives are listed as follows,

1. Identify the parameters for an application layer protocol for optimizing reading time
2. Develop a standard model for installing Zigbee in Utility network as cost optimizing without any disturbance to the communication

#### **1.5. Methodology**

Initially a study was carried out for identifying behavior of Zigbee based energy meter network with respected to the changes of several other parameters like day and night, location based communication speed etc. Then created some simulation models and studied the theory behind the communication delay and other stability problems. Then research was moved to study new situations like multiple meter readings at same time. And an economic analysis was also carried out within the research for selecting zigbee models for installing. Key points of the research are listed as following.

- ❖ Analyzing available network topologies
- ❖ Literature review
- ❖ Install a Zigbee network for testing
- ❖ Data Collection
- ❖ Theoretical Justification
- ❖ Simulation Justification
- ❖ Economic Analysis
- ❖ Result (Introduce a model for installing Zigbee in distribution network)

#### **1.6. Contribution**

The initial step was studying the available network topologies which can be used with RMR. And identify the advantages and disadvantages of those topologies. Select a suitable network topology which has high advantages with low disadvantages.

As per the past research and other literatures, Zigbee coordinator based network with GPRS was selected. In that network topology, there is a coordinator for coordinate all the meter end nodes. Energy meter is a data source which generates data at when requested or in specified frequency. And meter reading server is data collector and analyzer of all received data. The server will calculate monthly bill, load profiles, fault logs, power status etc. So coordinator has a special responsibility to maintain data link between energy meter and server as required. So coordinator should be much smarter for those functions. The coordinator should also work as a data concentrator. The responsibility of data concentrator is collect data from all meters which are within the group, and send stored data to the meter data collecting server. The data concentrator sends data to the base station via a customized data channel of a particular telecommunication service provider. Energy meters acts as a sensor network transmitting their data packets via RF channels and ad-hoc topology is called RF data network or Radio Island. The energy meter nodes having special facility called ad-hoc topology. Each and every Zigbee node having unique identification number called MAC address. It can be used for communication between each node.



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There were two types of Zigbee modules commercially available in the market called Zigbee and Zigbee Pro. Analyzed the difference between those type modules. The deviation between those models is RF power rating. Zigbee and Zigbee Pro modules have power ratings 1mW and 63 mW respectively. The power consumption and communication distance were measured in that stage by using those two.

A Zigbee based radio island was installed in Negombo area. Hundred number of Zigbee meters were installed. And a coordinator was developed with Zigbee coordinator, Arduino board and a GPRS modem. The coordinator was powered from 230 V LV line. Zigbee Pro (63 mW) module were used for the installation. AnteLECO DDSF949 meter model was used for that project. After installing all meter ends, the network was scanned using XCTU software. The XCTU software is programming software for Zigbee modules. Then all the meters were interfaced to the meter reading server. By the meter reading server, all the meters were able to communicate.

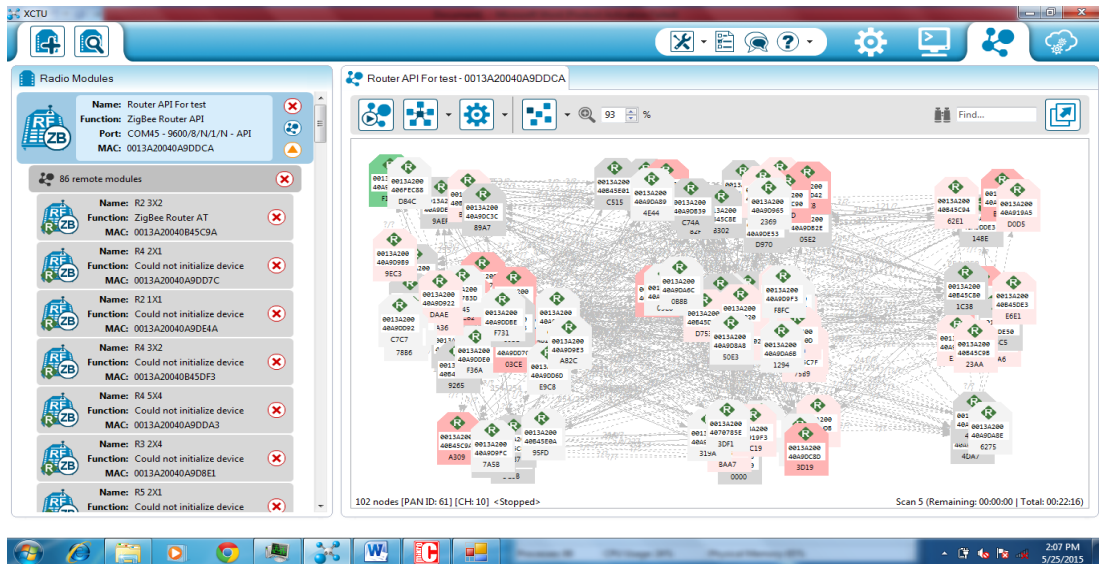


Figure 1-1 Observe Mesh network using XCTU software

Then some data were collected according to the communication delays and RSSI (Received Signal Strength Indicator) readings. Those data were plotted and analyzed the variations. A theoretical model was generated using “Shannon’s Equation” [2] and “Free Space Propagation Model” [1].

Communication speed related parameters were modeled using MATLAB Simulink software. Gaussian Noise was considered for the simulation. By changing the parameters of Gaussian Noise, the variation of communication speeds were simulated. The successful data communication rate also simulated using MATLAB Simulink software. This model was used for analyze behavior of communication speed with respect to some parameters.

Then the study was moved to identify the ability of multiple meter reading at a same time. A simulation model to calculate communication delay was developed by results of several simulations. By incorporating the algorithm to coordinator, it can calculate communication delay when requesting data from more than one meter ends. And that algorithm can be used to select best meter groups for reading in same time.

Economical study was also carried out. By that it was able to identify the cost reduction by using Zigbee (1 mW) modules instead of Zigbee Pro modules. And also it was able to identify the cost which is paying for the zigbee protocol stack. Finally

software was developed for generating zigbee pro installation position based on several parameters like minimum number of links, GPS positions using Visual Studio C#.

As a result of research, zigbee selecting software and communication delay calculating algorithm was generated.



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### 2. LITERATURE REVIEW

There are number of research for finding a best way to communicate with energy meter. Beyond that some research tries to optimize the communication delay, successful rate and other optimization parameters. This chapter reviews the different technological approaches, importance and the performance of RMR systems.

A problem in the meter reading is that massive amount of RMR nodes but consumes less data for reading. But real time connection is required for RMR. In addition to that reading retries can be accepted.

There are several number of communication mediums available for RMR. Some of them are Serial, PLC, Ethernet, Cellular, Wi-Fi, WiMax, ZigBee, Z-Wave, Bluetooth, Radio Frequency, Microwave etc [4].

But few of them can be only used for RMR. The wired communication is equipped with high data rates, high reliability than wireless communication. But wireless technology have some advantages like capability of expansions, suitable with remote area communication, low installation cost etc. Those are matched with network requirement of RMR. A comparison among different wireless technologies that can be considered for RMR applications is presented in Table 2-1 and Figure 2-1. With the development of technology, utilities are trying to interface with each and every equipment for monitoring and operating. Some nodes require communication links for continuous communication. And some nodes like LBSs, Auto recloses are required reliable link for communication because of the criticalness of the operations [4], [11], [12], [34].

Due to the growing number of meters, sensors (like power monitoring), and actuators (like LBS) which needs to be monitored and controlled continuously, utilizing wired technologies leads to a significant installation cost. With consideration of above factors, the wireless technologies are better communication method for RMR. However, wireless communication has some drawbacks like lower data rate, interference with other signals [4], [11], [12], [34].



Table 2-1 Comparison among different wireless technologies

Medium	Data rate	Distance	Initial cost	Frequency
Cellular	270 kbps	Long distance	High	900, 1800 MHz (2G), 2.1 GHz (3G)
Bluetooth	24 Mbps	100 m	Low	2.4 GHz
Zigbee	250kbps	100 – 1500 m	Low	2.4 GHz, 868, 915 MHz
WiMax	30-40 Mbps	Long distance	Moderate	2.3, 2.5, 3.5 GHz
Wifi	54 Mbps	100 m	Moderate	2.4 GHz
Z-Wave	100 kbps	30 m	Low	900 MHz

Source: [4]

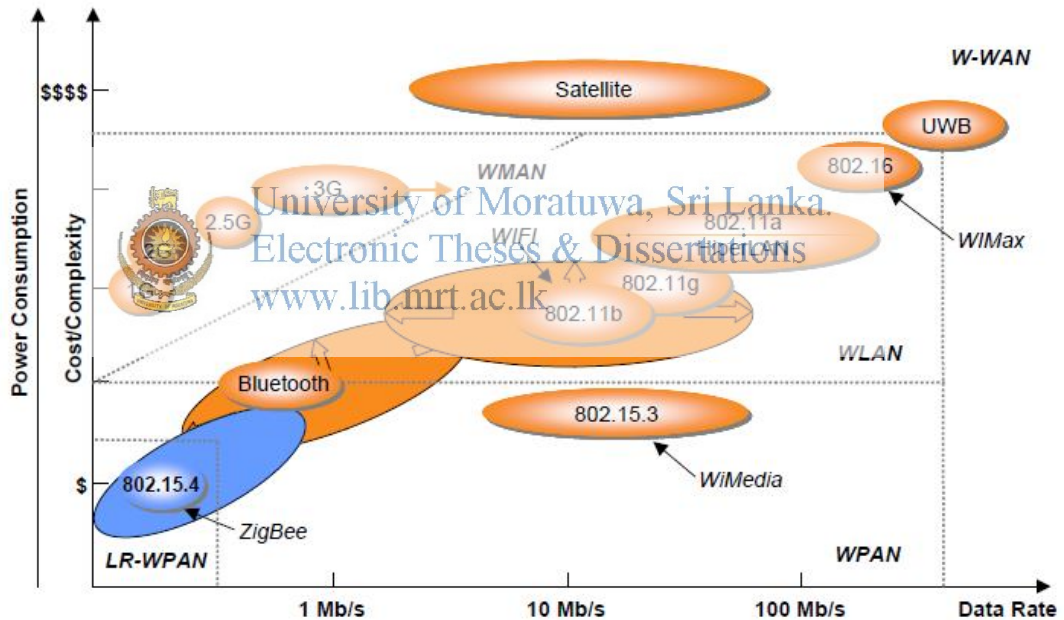


Figure 2-1 Cost and power consumption comparison of wireless technologies

Source: [5]



Thus Zigbee technology has several advantages when comparing with other wireless communication technologies. Therefore zigbee is more suitable for RMR than other wireless communications.

The advantages of zigbee are as follows,

- 1) Low cost communication device
- 2) Low power consumption
- 3) Support with mesh network
- 4) Less complexity for the users
- 5) Capable for expansions after installation
- 6) Capable to interface meter through RX and TX pins
- 7) Availability of security features like encryption, passwords
- 8) High flexibility for configuring zigbee nodes by configuration parameters
- 9) Covering an area can be expandable by repeaters.
- 10) Unlicensed 2.4 GHz band
- 11) Supporting Mesh Networks

A comparison between existing wireless communication technologies and the above mentioned characteristics is presented in Table 2-2. This table is also proof that Zigbee is the preferred communication system for RMR [4], [11], [12], [13].

Table 2-2 Comparison between wireless technologies

Specification	Cellular (2G, 3G)	Bluetooth	WiMax	Wifi	Zigbee
Low complexity		Yes			Yes
Low power consumption		Yes			Yes
Low cost		Yes			Yes
Simple interface for meters and sensors		Yes			Yes
Point to multipoint communication	Yes		Yes	Yes	Yes
Encryption			Yes	Yes	Yes
Capability to network expansions		Yes		Yes	Yes

Source: [4]

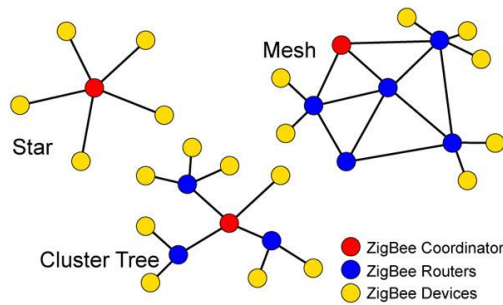


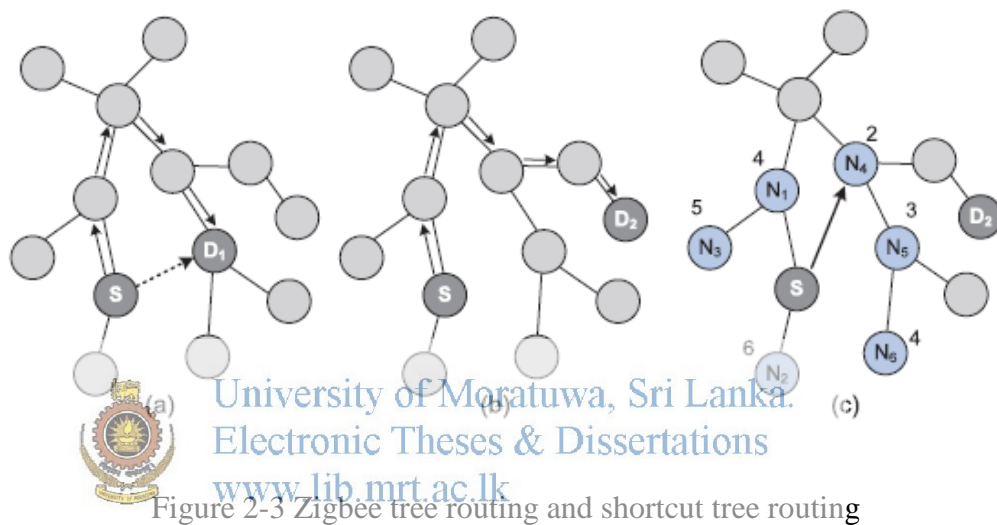
Figure 2-2 Zigbee Network topologies

Source: [7]

Up to 64,000 nodes can be managed by a zigbee network. In addition to that Zigbee is supported with tree and mesh network topologies with multi hop function and star network topology. Zigbee is supported with dynamic networks by routing, network management functions, addressing and many more functions [8].

In the Zigbee network, routing is a major function for maintaining the dynamic networks and as well as dynamic network traffics. In some zigbee communication applications, Zigbee Tree Routing (ZTR) algorithm is used for routing the network. In ZTR all nodes are assigned hierarchical addresses. Thus any node can decide whether received packet forward to the parent node or one of the children node by comparing destination address with its address. The key benefit of the ZTR is any packet can be delivered to its destination without any overhead of routing. So ZTR is reduced route discovery overhead in both bandwidth and memory by using like that address schemes. Due to those advantages of the ZTR, it is considered as a guaranteed protocol for networks with limited resource applications like Internet of Things (IOT), distribution monitoring and smart grid project. But in ZTR, every time it follows the tree structure to deliver data from sending node to destination address even if the destination is located near to the sending node as in Figure 2-3. Thus there is a space for optimizing the ZTR routing path further. To study the further optimization of ZTR, a study [6] was carried out. In that research, a new algorithm called shortcut tree routing (STR) was introduced. In that, by adding only the 1-hop neighbour information significantly enhances the path efficiency of ZTR. In ZTR, routing is based only on parent child tree structure. But in STR enhance the path efficacy beyond the ZTR by checking the capability of shortcutting the tree routing

path with neighbour nodes in mesh networks as Figure 2-3. In STR, each node has a capability to select routing path direction to the destination. So in STR, the sender or the intermediate node try to find smallest remaining tree hops to the destination without considering of acting mode of next hop node whether it is a parent, one of children, or neighbouring node. In addition to that it says STR is fully compatible with the Zigbee standard which is applied the different routing strategies according to each node's status. In the conclusion of the research, they say STR increases the packet delivery ratio [6].



Source: [24]

In Zigbee, as a RF technology range of transmission and reception is limited according to the power ratings. But in Zigbee has special characteristic called multihop and mesh, can deliver data to long distance. That part is done by the routing protocol. Thus, routing protocol plays a vital role to establish communication within the network and is also used to discover proper routing path between sender and destination. For creating correct and efficient routing path between nodes in Zigbee, routing protocol types like AODV (Ad Hoc On-Demand Distance Vector), DSDV (Destination-Sequenced Distance Vector) etc. are the most popular routing protocol for Zigbee. In some research comparison had been done between them [3]. In that research, a simulation had been done using AODV and DSDV. AODV is an on demand protocol while DSDV is proactive/table driven protocol. In AODV routing path updates are executed when required. But in DSDV routing tables are updated in

periodical manner. Thus in DSDV, network congestion can be occurred due to high traffic in the network when data rate increases. Therefore, it was concluded that AODV performs routings much better than DSDV in ZigBee networks. In the research, it had been compared both the protocols using graphs, it is seen that AODV consumes much less energy than DSDV. Because in DSDV it is updates routing tables in periodical manner even when there is no communication. But AODV updates routing table only in traffic [3].

In most research, they try to optimize network layer as in Figure 4-27. But in RMR nodes are not moving. So the communication speed can be optimized using GPS based algorithm in Application layer.



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### 3. ENERGY METER AND RMR

#### 3.1. Introduction to Electricity Energy Meter

Electricity energy meter, energy meter, electricity meter, electric meter, electrical meter called same item and is measurement equipment to measure electricity usage of consumers. The various types of tariff categories like domestic, general purpose, industrial etc are used in Sri Lanka. So utility needs to consider measurement requirement when selecting a meter to the consumer. In most of the time, the meters are installed in consumer premises. Basic measurement unit of the meter is kWh. But now a day, lot of data like kVA, import and export kWh, voltage, current are measured using energy meters. Some extracted data from energy meters are used for several type of analysis like data clustering, power quality monitoring etc.

As per the requirement up to now, several type of energy meters like electromechanical meters, electronic meters, smart meters, prepaid meters, demand response meters, Time Of Day (TOD) meters, net meters etc are used in electricity industry. Electricity meters other than electromechanical type meters, are incorporated with a microprocessor or electronic chips with considerable processing power.

TOD meters are incorporated with special function to measure electricity usage in predefined time periods of day with electricity demand. Those types of meters are allowed to measure or measure and calculate energy usage separately according to the time periods of the day.

Import and export energy can be measured using net meters. It's calculated net sum of energy usage. Those type meters are required when consumer is having his own generation instead of only usage. In net metering context, integrating the communication system with meter is useful for both customer side and utility side. So user portal is useful for the net metering user to manage their solar and other generations.

Prepaid metering is another trend for the electricity industry. Prepaid meters doing essential function in prepaid electricity measuring and operation. There should be a cutoff relay for that operation. Those types of meters are functioning with and without direct communication link to the central server.

Smart meter is a new trend for electricity industry. It's incorporated with a high processing power processor with a considerable memory. In most of time, all above functions are incorporated with those types of meters. And those types of meters are capable to connect with communication interface with some protocol.

IOT (Internet of Things) platforms are developing day by day and it is also a new trend from energy metering. The meter integration to the Internet is a must in the IOT platforms. In that, meters are connected to the internet for data uploading. Many type of data analysis can be done by collected data form meters.

#### 3.1.1. Meter Data Communication Protocols

Energy Meters are currently offer with four methods of communications, which are, the simple pulsed output, the optical port, RS485 and RS232 port. But the energy meter interface development is not limited to above communication methods. It will be incorporated with new interfacing methods according to the new developments. Although the hardware for these methods is standard among manufactures, the protocols and the data are not standard. Currently all manufacturers offer their own reading and programing software and different communicating chips in order make this transparent to the user. In the energy meter data communication context, many types of protocols such as Modbus, DLMS, IEC 62056-21 are used. IEC 62056-21 can be considered as standard meter communication protocol. In the electricity distribution industry, the IEC 62056-21 is used for data communication. But some meter manufactures are not supported with IEC standards. There is a function called readout for extracting some data set which is usually required.

In IEC 62056-21 Readout

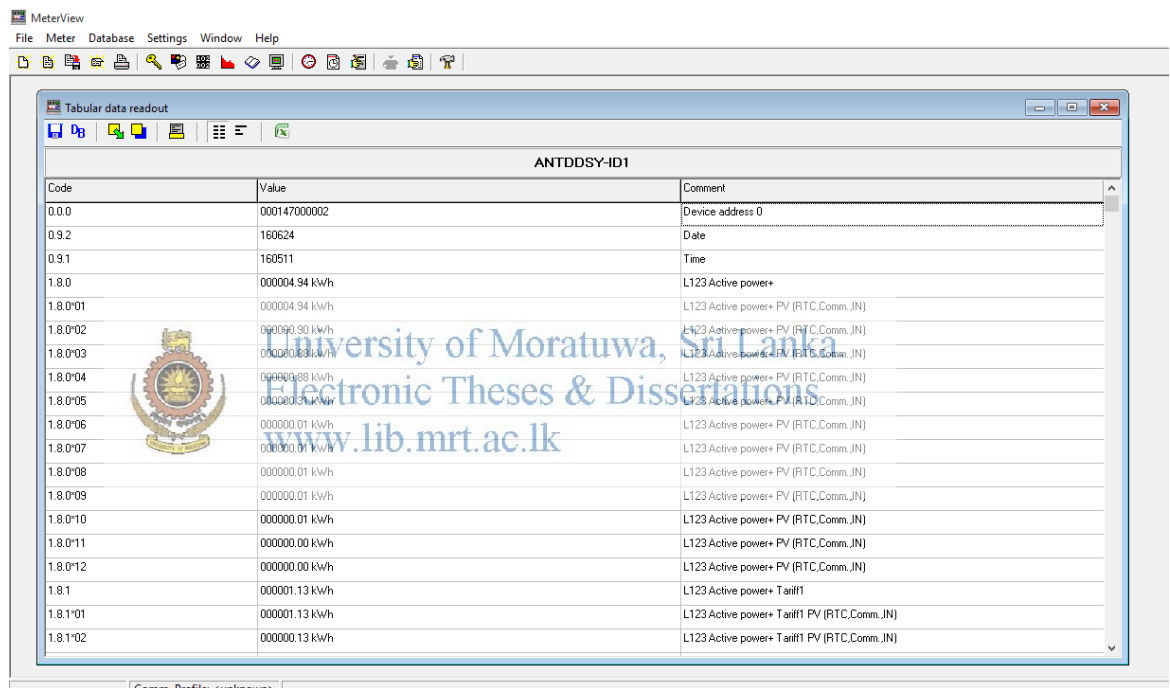
>>Send login command to meter

<<Meter model

>>Send request to Readout

<<Readout data

The data are stored in meters with reference to the registers. There is another function to read registers separately. In addition to that security features are available in that protocol. Those registers are managed by some other standards like OBIS (Object Identification System).



Code	Value	Comment
0.0.0	000147000002	Device address 0
0.9.2	160624	Date
0.9.1	160511	Time
1.8.0	000004.94 kWh	L123 Active power+
1.8.0*01	000004.94 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*02	000000.90 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*03	000000.83 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*04	000000.88 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*05	000000.81 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*06	000000.01 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*07	000000.01 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*08	000000.01 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*09	000000.01 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*10	000000.01 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*11	000000.00 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.0*12	000000.00 kWh	L123 Active power+ PV (RTC,Comm.JIN)
1.8.1	000001.13 kWh	L123 Active power+ Tariff1
1.8.1*01	000001.13 kWh	L123 Active power+ Tariff1 PV (RTC,Comm.JIN)
1.8.1*02	000000.13 kWh	L123 Active power+ Tariff1 PV (RTC,Comm.JIN)

Figure 3-1 Meter Reading Software

The readout data are attached in appendix A.

### 3.1.1.1. Introduction to Object Identification System

When multiple meters are connected to the central meter reading server, either server should be supported for multiple protocols and register list or all the meter should be supported for standard protocol and register list. There is a standard protocol for meter reading called IEC 62056-21. The requirement of standard register format was also increased with increasing the functionality of meters. Some meter manufactures

or countries used their own register formats and some are proprietary. A register format called EDIS (Energy Data Identification System) was widely recognized systems in Germany. In that situation OBIS (Object Identification System) standard was developed as the standard format of register list. The OBIS standard was developed base on EDIS.

In the OBIS format, it uses 6 value groups in a hierarchical structure as following.

A-B:C.D.E\*F

The group A defines the energy type measured (0=abstract objects, 1=electricity, 6=heat, 7=gas, 8=water, ...). It is reserved space for future extensions.

The group B defines the measuring channels. Multiple channels generating measurement results of each device can be separated the results into the channels.

The group C defines the physical quantity measured (energy, voltage, current, frequency, temperature,).

The group D defines the processing methods and country specific code.

The group E specifies the measurement type defined by groups A to D into individual measurements (like switching ranges)

The group F separates the results partly defined by groups A to E. The typical usage is the specification of individual time ranges. (Like TOD)

Groups B to D have code space for manufacturer specific identifiers.

Table 3-1 Some registers

1.8.0	Positive active energy (A+) total [kWh]
0.0.0	Meter ID
0.9.2	Date
0.9.1	Time
31.7.0	Current [A]
14.7.0	Frequency [Hz]
32.7.0	Voltage [V]



### 3.1.2. Read Meter Through GPRS (Mobile Network)

In that, GPRS modem is attached to the meter and data can be polled from the server side. There are two commands (login and readout request) to get readout message from meter as in IEC 62056-21.

So usually it takes around 1.5 min time for reading. But in coordinator based systems like Zigbee network, the time can be optimized.

There are some broadcast and unicast communication technologies such as PLC, GSM, GPRS, Wi-Fi, Opticalfiber and Zigbee which are widely used in RMR.

### 3.1.3. GPRS

GPRS (General Packet Radio Service) is widely deployed and used mobile data service on GSM network with second (2G) and third (3G) generation cellular communication systems. It is a packet oriented mobile data service. When 2G technology combined with GPRS is sometimes called as 2.5G. In the GPRS communication charging criteria is based on utilized data amount. It can be either upload or download. GPRS communication cost is less than circuit switched services because communication channels are used as shared basis. But in GPRS certain quality of service (QoS) is guaranteed.

Theoretically in GPRS communication speed can reach up to 115 kbps. But in practically it is reduced up to around 35 kbps [1, 21].

### 3.1.4. PLC

PLC (Power line communication) can be used with electrical power distribution line, transmission line, indoor communications etc. In PLC data is propagate through electrical lines by using some protocols while energized with Alternating Current (AC).

When considering electrical distribution system, some factors like propagation speed, frequency, voltage level, the existence of transformers, distance etc can be affected to the successful communication rate.

Some meter types are used PLC communication as a communication medium.

### 3.1.5. Radio Frequency

In RF (Radio Frequency) communication, electromagnetic waves are used and frequency range is around from 3 kHz to 300 GHz.

There are two parties involved in RF communication called RF Transmitter and RF receiver. An antenna is used to receive signals. But when antenna is opened to air, then antenna will catch up lot of RF signals. So a filter must be used to select only required signal.

The RF communication distance is depend on transmission mode, noise level, transmitter power, receiver quality, type, size, and height of antenna, and interfering signals.

Bluetooth, Zigbee, Wifi, WiMax etc can be classified depending on the signal power and frequency band as short range RF technologies.

In this study, Zigbee was used as the communication medium. Zigbee is supporting mesh networks. So data hopping can be performed in the network. Thus low power transmitters are enough because only the requirement of RF module in network is connected to the nearest nodes. The Zigbee communication is based on IEEE802.15.4 standard. The Zigbee based RMR, is worked as a sensor network. But bandwidth of zigbee is very low like 20 kbps at 868 GHz and 250 kbps at 2.4 GHz.

Other point to point and star RF network topologies can be used in RMR systems in various ways [8].

### 3.1.6. Optical fibre Communication

In optical fibre communication, information is sent over a fibre by converting electrical signal to a light. The fibre is a long, thin strand of glass (silica) or plastic. It is flexible, transparent and slightly thicker than that of a human hair.

LEDs (Light Emitting Diode) or LDs (Laser Diode) are used to convert electrical signal to optical signal. As well as, PIN Diodes (Silicone or InGaAs based p-i-n Diode) or Avalanche Diodes (Silicone or InGaAs Diode) are operated optical to electrical converter. By LDs and Avalanche Diodes can be achieved high baud rate in communication.

Low attenuation, very high bandwidth, low weight, small size, high secured, no electromagnetic interference, long distance communication are the advantages of the optical fibre communication.

Optical fibres can be laid with electrical wires and can be used for communicating. For RMR, optical fibre converter should be installed nearest to the meter. [22, 23]



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## 4. DEVELOPMENT OF TEST BENCH FOR ZIGBEE NETWORK

As an initiation of RF based RMR to LECO, a RF Meter Island was installed @ Negombo area.

Selection criteria of the area

The Negombo area was selected because of the following reasons,

- Customer density is suitable for Mesh network
- Ability to check reliability from radio interferences to the RF Network (basically consider interference from radar system and telecommunication interferences)
- Flatness of land area
- Easy accessibility for LECO Engineering team



Ability to study disturbance from moving vehicles to the RF network

Accordingly, Negombo area was selected for installing RF Radio Island with the help of branch officers.

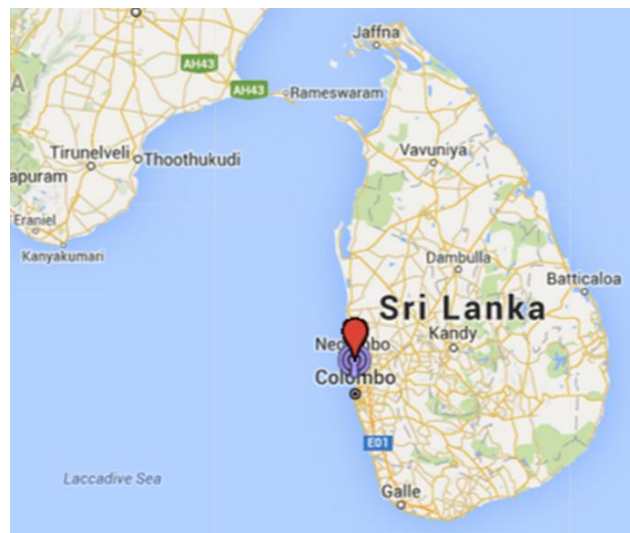


Figure 4-1 Location

Three number of transformer areas in Negombo were proposed for the installation.

Table 4-1 Selected Transformers

	<b>Transformer ID</b>	<b>Number of consumers</b>
1	BZ0501	484
2	BZ0509	198
3	BZ0513	319

The BZ0501 Transformer area was selected by field visits. The communication distances were measured in that area.

Table 4-2 Result of communication distance measurement

<b>Zigbee model</b>	<b>Power rating</b>	<b>Practical communication Distance</b>
Zigbee Pro	63 mW	190 m
Zigbee	1 mW	30 m

As the initial step, 100 number of Zigbee meters were installed in that transformer area. For that AnteleCO DDSF949 meter model was used for the installation.



Figure 4-2 Selected locations

#### 4.1. AnteLECO DDSF949 meter

The meter is having following functions,

- TTL interface (IEC 62056-21)
- 5V supply output for modem
- Connection/ Disconnection
- Single phase meter
- Optical interface for programming and reading
- Import Export measurement



Figure 4-3 DDSF949 Meter

##### 4.1.1. Communication module

Zigbee pro units were used as a communication module in meter with in-house designed PCB.



Figure 4-4 Zigbee Routers

#### 4.1.2. Coordinator

Coordinator is included with a Zigbee pro module, GPRS modem and Arduino board as Figure 4-5. Initially coordinator was designed with a pipeline function only. That means coordinator function was only create a communication path to the required meter. The modem was worked as a GPRS socket server. Some other photos are attached in Appendix B and program is attached in Appendix C.

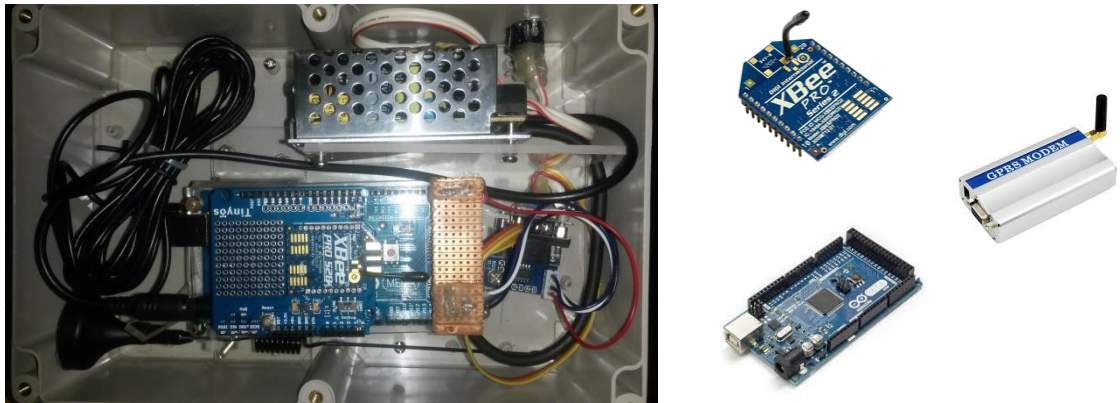


Figure 4-5 Coordinator

After the installation, all the meters were interface to the central server. As an initiation of study, RSSI and communication time delay were logged using developed software and observe the RF links between each zigbee meter ends.

Mesh network is shown in figure 4-6,



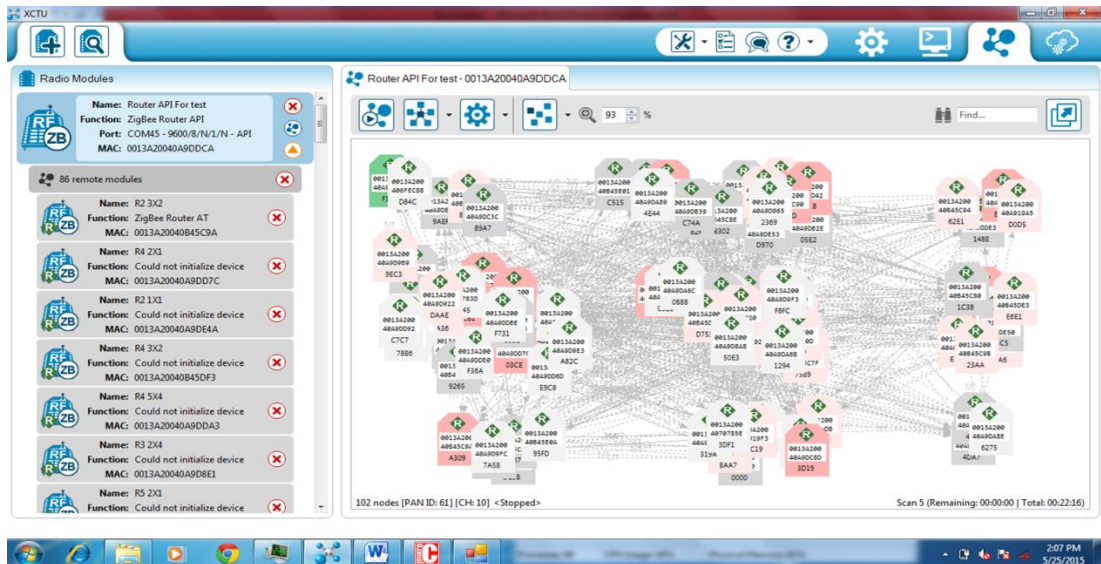


Figure 4-6 Observation of mesh network on XCTU software

All 100 numbers of nodes had been connected to the coordinator through mesh network. Then LQI (Line Quality Index) in each link is extracted from XCTU software. Some of the data are shown in figure 4-7 and all the data are attached in Appendix D.

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	B	C	D	G	H	I	J	K	L	M	N	O	P	R	S	T	U	V	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	
1	LQI	A3DB40	BFECE8	70783D	70785E	70786D	A7DF58	A31778	A319A5	A319F3	A3D8A8	A3D8E1	A3D922	A3D965	A3D987	A3D98B	A3D9B9	A3D9C5	A3D9E3												
2	A3DB40		255																												
3	BFECE8			241				188	255		242						254	255				255									
4	BFEDE1																								254						
5	70783D																														
6	70785E	244							12		255						87	250				255				59					
7	70786D							110		251				255	40	252	255	255													
8	A7DF58																					254			166						
9	A31778																														
10	A319A5													220	253	255	254														
11	A319F3																														
12	A3D8A8	255									245																				
13	A3D8E1																														
14	A3D922																														
15	A3D965	225			255																										
16	A3D987	255	255																												
17	A3D98B			255						207	255																				
18	A3D9B9																														
19	A3D9C5	244																													
20	A3D9E3				238			255	255																						

Figure 4-7 LQI variation



## 4.2. LQI

There are many types of indications or measurement, associated with Zigbee technology for measuring quality of the communication. LQI (Link Quality Indicator) is also an indicator for measuring strangeness of communication links. It is a calculated value based on received signal strength as well as the number of errors received. In a data corruption situation, the indication can be used to identify whether a corrupt packet resulted from low signal strength or from high signal strength plus interference.

According to the IEEE 802.15.4, LQI reading is varied in between 0 and 255. With the combination of RSSI and LQI readings, it can be obtained a good image about the last communications.

When Zigbee network is operating with strong signal without much noise may give high RSSI and low LQI.

When the network is operating with a strong noise coming as an interferer, may give high RSSI and LQI.

When the network is operating with low noise environment with weak signal may give low RSSI and LQI.

When the network is operating with a strong noise environment with weak signal may give low RSSI and high LQI.

When the network is operating with a low noise environment with strong signal may give high RSSI and high LQI and can be considered as good condition [18].

For the RSSI and communication delay data collection, developed software (figure 4-8) was used.

The logged data were plotted using excel. The data were collected for 24 hour period in 20 min time intervals. Some of the collected data were tabulated in Table 4-3 and Table 4-4.

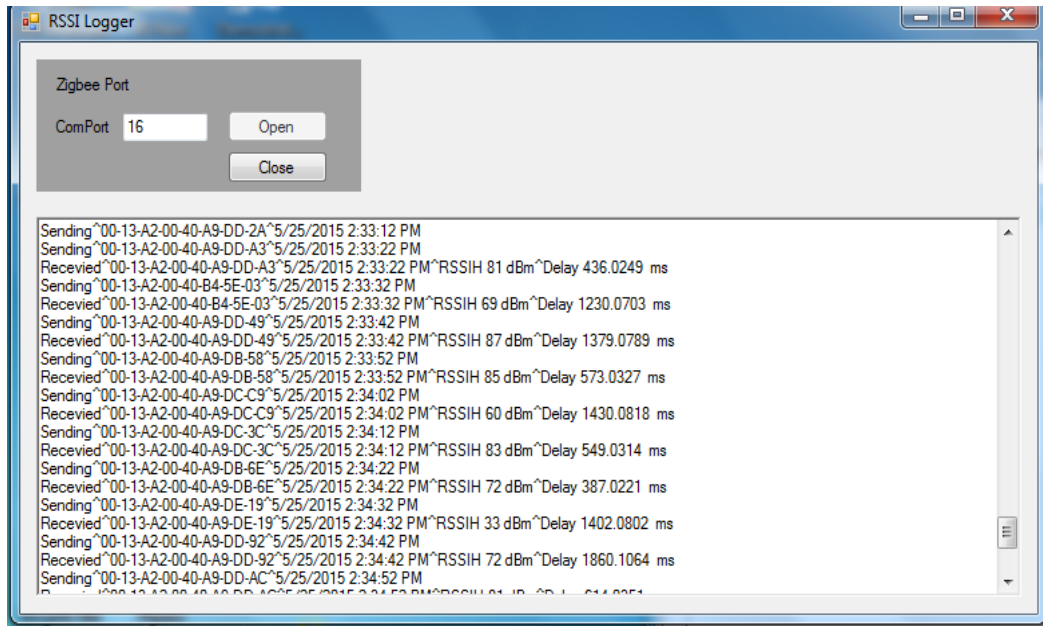


Figure 4-8 RSSI Logger Software

Table 4-3 Communication delay (Given in ms) Vs time stamp and meter ID

		Time Stamp (min)										
		0	20	40	60	80	100	120	140	160	180	200
Meter ID	1	2002	544	492	1192	595	712	555	1133	967.2	603.8	468
	2	503	1388	1278	1252	766	641	1161	1238	889.2	1357	592.8
	3	1916	400	400	57	55	53	53	265.2	46.8	46.8	
	4	623	814	400	847	547	503	410	459	920.4	1154	468
	5	490	397	418	352.8	352.8	352.8	384	344	312	358.8	296.4
	6	840	858.1	858.1	858.1	1001	1252	1339	858.1	1232	811.2	608.4
	7	235	80	64	66	66	62	69	65	62.4	62.4	62.4
	8	375	295.6	295.6	295.6	295.6	295.6	361	312	280.8	343.2	327.6
	9	1711	344	345	366	351	355	366	314	358.8	296.4	312
	10	827	1003	1491	1200	973.1	936.1	1388	1294	1326	1294	795.6
	11	242.6	242.6	242.6	276	296	313	327	287	312	530.4	327.6
	12	525	496.1	486	453	1748	458	484	496.1	496.1	496.1	496.1
	13	599	898.1	1004	1239	1019	754	1169	1315	1186	1186	920.4
	14	555	951.1	545	595	1205	636	605	776	858	499.2	826.8
	15	358	357	387	327	343	351	295	297	358.8	327.6	312
	16	64.12	72	72	73	78	74	73	62.4	62.4	62.4	62.4
	17	790	956.1	736	484	634	482	617	514.8	1217	1357	436.8
	18	1420	1145	973.1	961.1	1478	1127	972.1	1145	1014	1248	1076
	19	1076	1120	1323	1254	1283	1197	865	546	1342	1123	811.2
	20	1204	1204	1204	1204	1204	750	1188	1279	1310	1264	1045

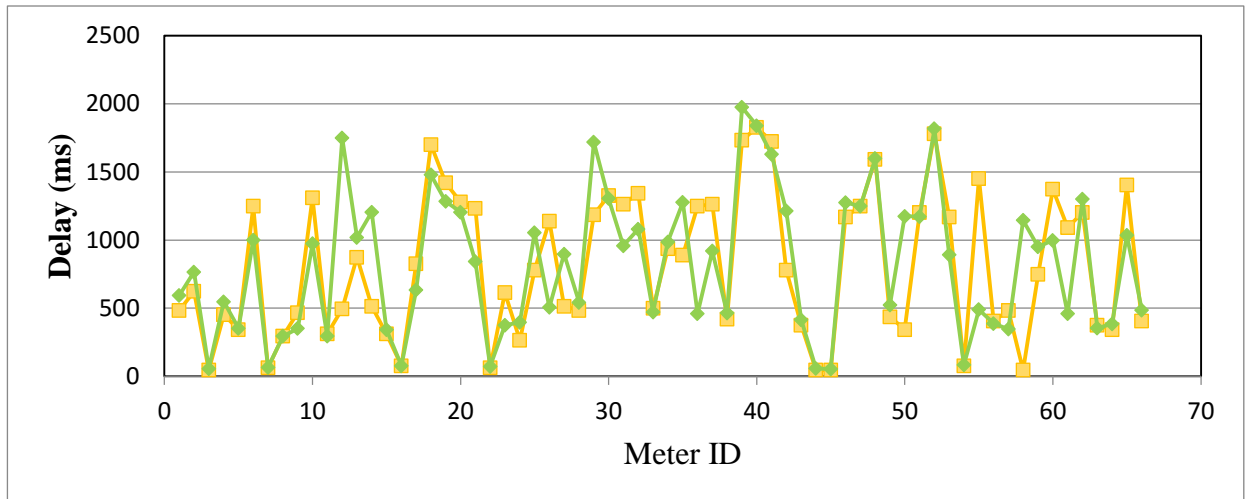


Figure 4-9 Communication delay variation Vs Meter ID on 80 min and 1320 min time stamps

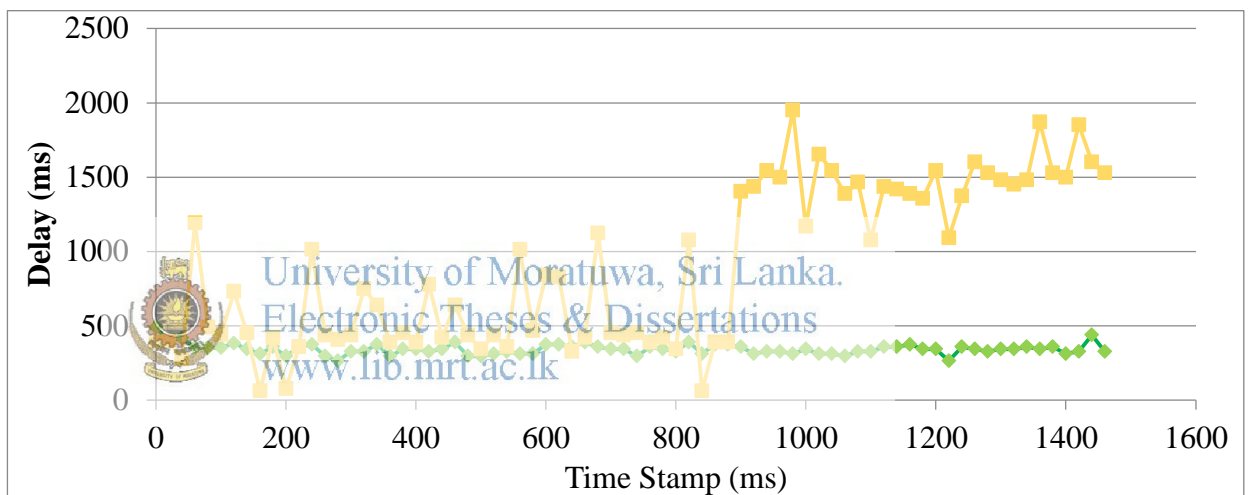


Figure 4-10 Communication delay variation Vs Time Stamp for 6th and 56th Meters

According to the Figure 4-9, variation of communication delay was affected to nodes in uniform way in both time stamps. But according to the figure 4-10, variation of communication delay was affected to both nodes in different way in day time and night time.

### 4.3. RSSI Measurement (dBm)

RSSI (Received Signal Strength Indication) is a measurement of received signal quality. Its measuring unit is dBm (sometimes decibel-milliwatts or dBmW). The

decibels (dB) value of the measured power referenced to one milliwatt (mW) is called dBm. And also dBW means the dB value referenced to the 1000 mW.

This parameter is used in fiber optic networks, radio networks etc. The parameter is having special capability to express both very low values and very high values. So it can be considered as convenient measurement of absolute power.

$$x = 10 \log \frac{P}{1 \text{ mW}} \text{ --- Equation 4-1}$$

Where

P= Power (mW)

x= RSSI (dBm)

By the equation 4-1, it can be calculated RSSI from power and vice versa.

Table 4-4 RSSI variation VS Meter ID and Time Stamp

		Time Stamp (min)										
dBm		0	20	40	60	80	100	120	140	160	180	200
<b>Meter ID</b>	<b>1</b>	-69	-69	-70	-69	-87	-69	-85	-69	-69	-70	-72
	<b>2</b>	-79	-80	-63	-69	-71	-63	-88		-65	-79	-63
	<b>3</b>	-89	-69	-78	-77	-77	-77	-77	-75	-69	-75	-75
	<b>4</b>	-78	-78	-79	-67	-79	-79	-71	-80	-78	-79	-79
	<b>5</b>	-77	-78	-78				-68	-69	-67	-67	-66
	<b>6</b>	-70				-78	-70	-69		-77	-80	-66
	<b>7</b>	-69	-66	-71	-73	-74	-70	-76	-67	-74	-66	-62
	<b>8</b>	-69						-70	-70	-69	-70	-69
	<b>9</b>	-73	-79	-77	-78	-73	-75	-80	-86	-82	-82	-77
	<b>10</b>	-78	-79	-82	-81	-72	-80	-80		-51		-82
	<b>11</b>	-37	-55	-38	-54	-38	-38	-56		-38		-51
	<b>12</b>	-72			-79	-78	-80	-81	-85	-87	-75	-76
	<b>13</b>	-63		-65	-65	-65	-62	-64				
	<b>14</b>	-76	-75	-35	-76	-76	-77	-77	-76	-75	-82	-76
	<b>15</b>	-78	-81	-83	-75	-85	-74	-67	-74	-75	-72	-71
	<b>16</b>	-72	-65	-64	-64	-65	-64	-63	-64	-63	-61	-63
	<b>17</b>	-72										
	<b>18</b>	-57		-57	-58	-58	-58	-58		-56	-57	-80
	<b>19</b>	-72	-74	-71	-72	-72	-71	-72	-70	-71	-71	-72
	<b>20</b>	-80	-70	-57	-57	-80	-67	-78	-79	-68	-55	-54

The collected data were plotted in excel as figure 4-11, figure 4-12.

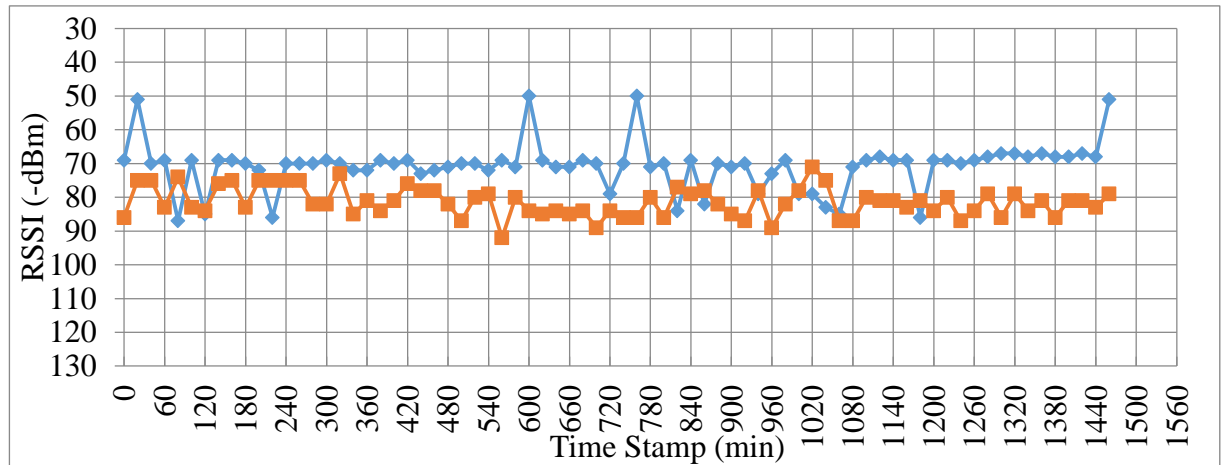


Figure 4-11 RSSI variation Vs Time Stamp for 1st and 23rd Meters

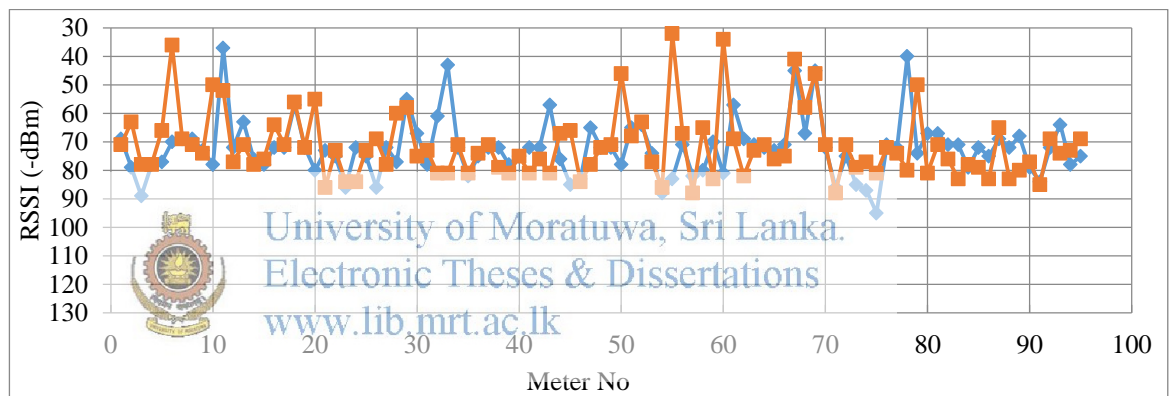


Figure 4-12 RSSI Variation Vs Meter No for day time and night time

According to the figures, the mesh network seems to be in a very strong condition. So Zigbee Pro modules can be replaced by Zigbee modules to reduce the cost. It will directly affect to the total cost. So it's better to create a function for Zigbee module selection when installing. It will be helpful for future installations.

As central server for meter reading, LECO is using in-house developed software. Another study was carried out using extracted data from that system. When its user requested to read meters, then server will send meter reading request. If it will fail (not received data within 1.5 min), then server tries to reattempt it. In that way server

need to reattempt several times if communication link is not much strong. According to that data usage will be varying.

#### 4.4. Data usage of modem

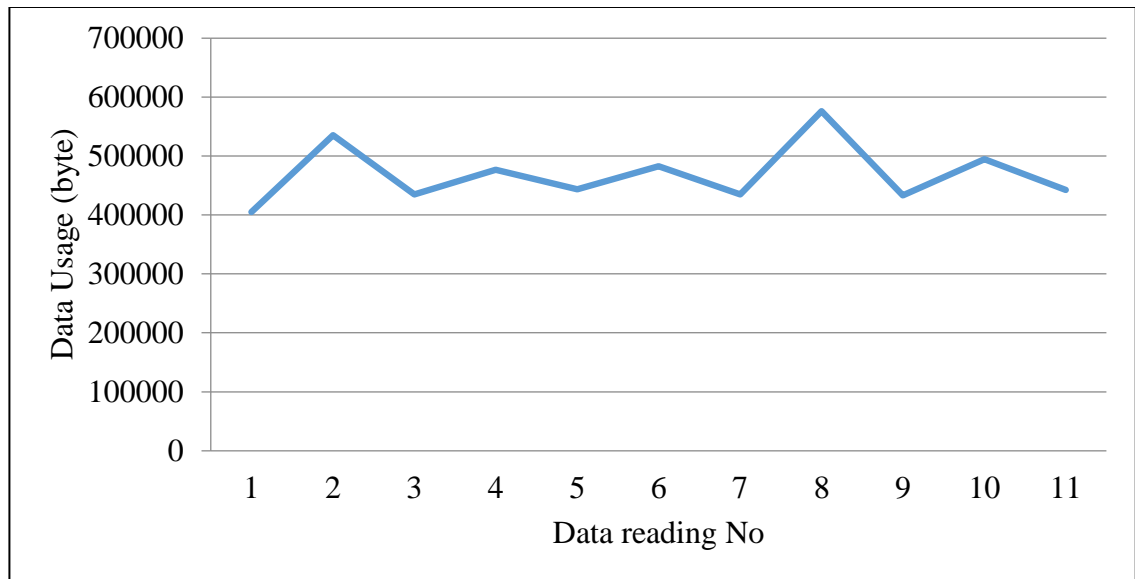


Figure 4-13 Data usage for 100 meters Vs Reading No

As per the figure 4-13 data usage is varying with time to time. It can be happen by increasing the no of attempts.



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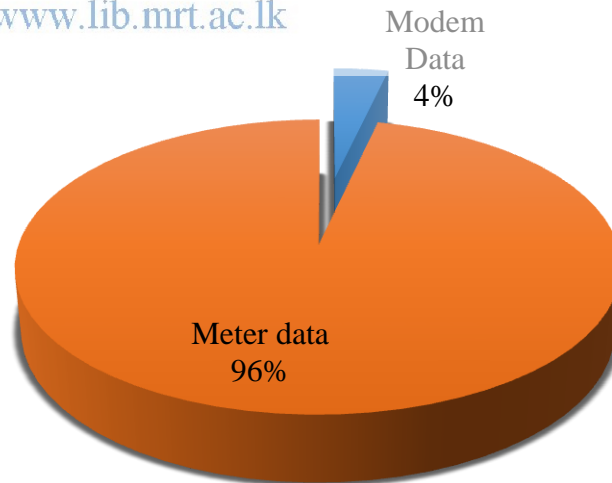


Figure 4-14 Data Usage for meter reading

As per the graph in figure 4-14, 4% (Every 10 min GPRS modem use 336 bytes) of data is used by modem functions. But in a Zigbee network that 4% is the total

modem data consumption for 100 numbers of meters. So for a meter modem data usage is reduced up to 3.36 byte in 10 min periods.

Number of Attempts to read meter

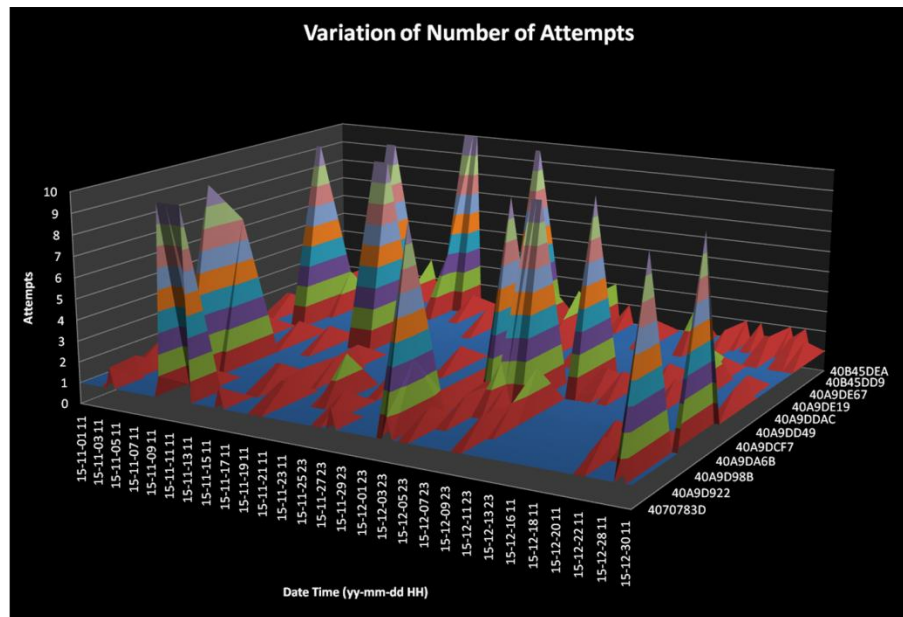


Figure 4-15 Number of Attempts to read meter

As per the figure 4-15, number of reattempts is varying in an acceptable limit. That means successful rate of reading is in a high value. So it is also implied successfulness of the zigbee network.

Up to now behavior of zigbee network is studied using practical data. Then Matlab Simulink model was generated for simulating zigbee meter network stability with the RF noises.

#### 4.5. MATLAB Simulink

Simulink is an advanced tool provided by MATLAB in order for the user to build models by both block diagrams and instruction codes. Matlab and Matlab Simulink are used by many engineers and scientists. It can be used to analyse and simulate systems with various inputs and the results are observed over time. The Matlab Simulink is equipped with a customizable block libraries, graphical editor, and solvers for modelling and simulating dynamic systems. The real world dynamic systems like electrical circuits, communication channels, shock absorbers and many other electrical, mechanical, and thermodynamic systems can be simulated using this



software. In this project MATLAB Simulink is used to create the block diagram, using the Simulink model editor simulate the variations.

In developing models, Shannon's Equation [2] and Free Space Propagation Model [1] were used.

Shannon's Equation:

$$C = W \times \log_2 \left( 1 + \frac{S}{N} \right) \text{ --- Equation 4-2}$$

Where

C= Channel capacity (bit per second)

W= Bandwidth (Hertz)

S = Signal power (Watts)

N = Noise power (Watts)

Channel is subject to White Gaussian noise of power N

#### 4.6. White Gaussian Noise

The Gaussian noise is a statistical noise. It has a probability density function the normal distribution. So noise levels extracted from Gaussian noise can be called as Gaussian distributed noise. White Gaussian Noise is special case of Gaussian noise. In that values at any pair of times are statistically independent and identically distributed.

#### 4.7. Free Space Propagation Model

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \text{ --- Equation 4-3}$$

$$C = f\lambda \text{ --- Equation 4-4}$$

Where

- $P_r$  = Received Power
- $P_t$  = Transmitted Power
- $G_r$  = Receiver Antenna Gain
- $G_t$  = Transmitter Antenna Gain
- L = Loss Factor ( $\geq 1$ )
- d = Distance (m)
- $\lambda$  = Wavelength (m)



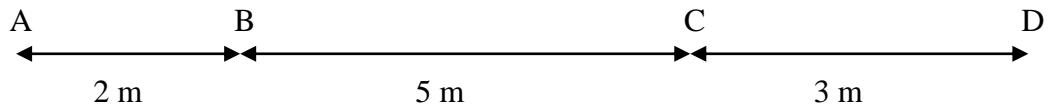
Consider situation like  $P_r$ ,  $G_r$ ,  $G_t$ ,  $L$  and  $\lambda$  are constant. And sending data to 10 m distance. So equation can be consider as,

$$P_t = kd^2 \text{ --- Equation 4-5}$$

Where k is a constant.

1. Through Mesh network
2. Through Direct connection

Through Mesh network



Required power

Table 4-5 Transmit power

A to B	$k2^2$
B to C	$k5^2$
C to D	$k3^2$
Total	$38 \times k$

Through Direct connection



Required power

$$k10^2 = 100 \times k$$

So total transmit power requirement can be reduced when using mesh networks.

A simulation model was built using Free Space Propagation Model and Shannon's Equation.

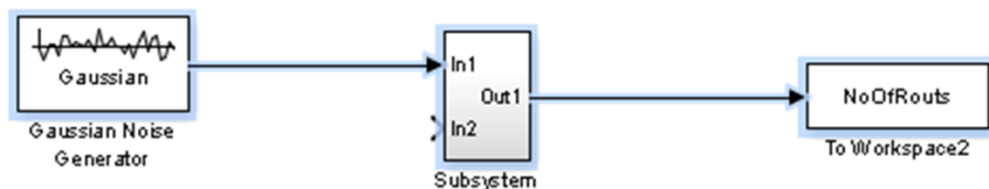


Figure 4-16 Simulation Model

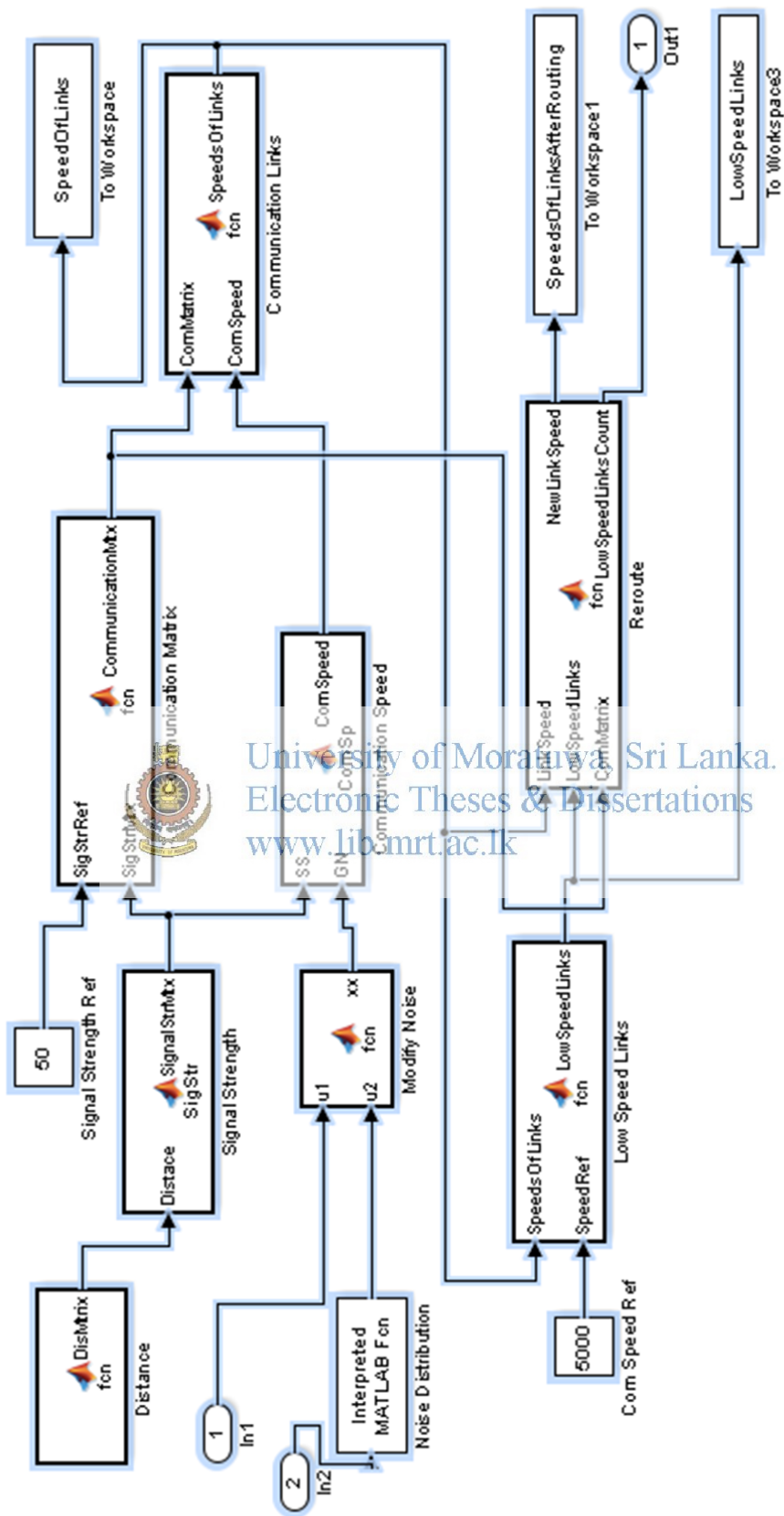


Figure 4-17 Simulation Model

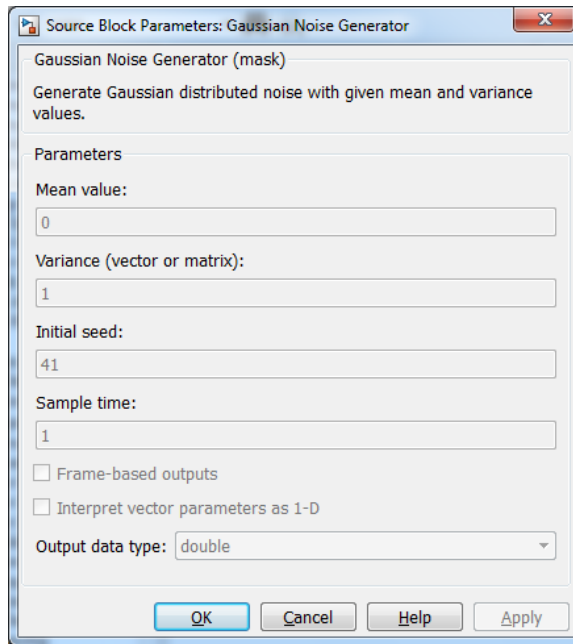


Figure 4-18 Configuration Window of Gaussian Noise Generator

In the simulation DisMatrix is calculated by the inputs of coordinates of nodes in Table 4-6. Noise distribution is generated by Gaussian noise.

Table 4-6 Coordinates of Positions

	X (m)	Y (m)
1	100	100
2	100	200
3	300	100
4	500	100
5	400	300
6	300	300
7	100	400
8	300	500
9	400	600
10	100	600

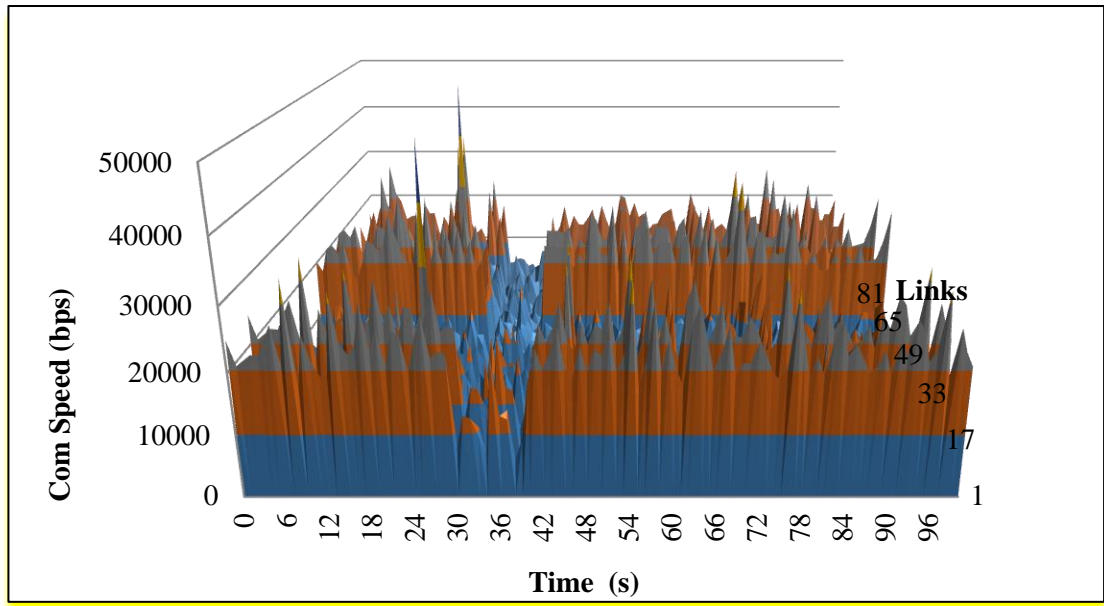


Figure 4-19 Communication Speed Variation Of Links Vs Time

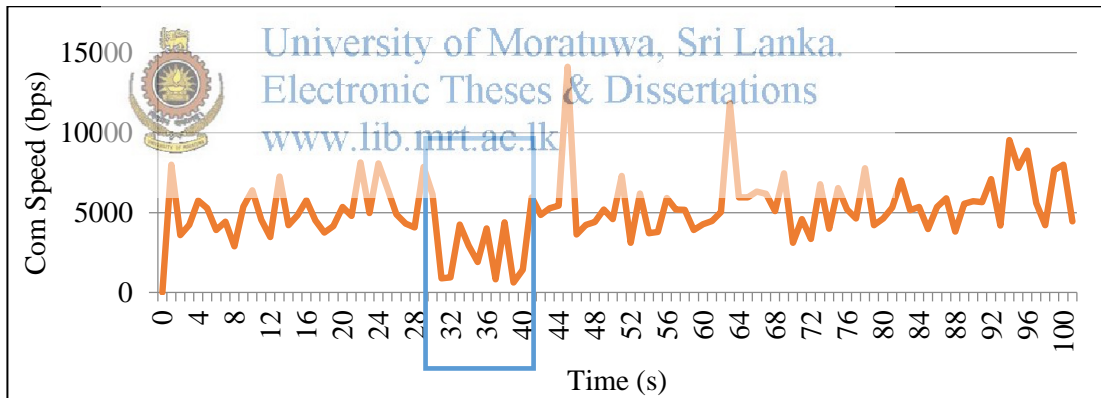


Figure 4-20 Communication Speed of 7th Link Vs Time

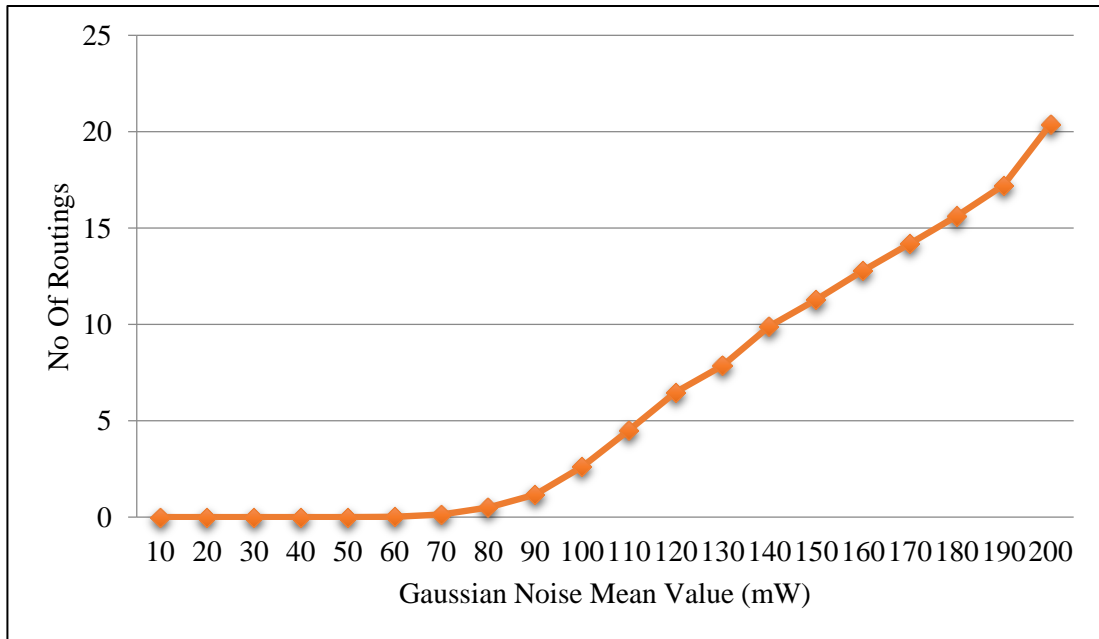


Figure 4-21 Number of Routings Vs Gaussian Noise Mean Value

In Figure 4-19 and Figure 4-20, noise level has been increased from 30 to 40 s interval. It shows that communication speed reduces when noise level increases. Also by that simulation as Figure 4-21, it can be identified that number of routings will be increased with the noise level. That can be a reason for RSSI variation in night and day time in Figure 4-10.

So Zigbee based meter reading is perfectly working with one by one reading. For reading one meter, averagely it is consumed 1.5 min. Obviously for reading 100 meters in same way, it is consumed around 150 min. So it was tried to read multiple zigbee meters in same time. As a test environment, it was tried to communicate with multiple zigbee units in same time (Table 4-7).

Up to 8 nodes, all zigbees were responded within the 1 min period. When beyond the 8 nodes, it was reduced the received percentage. That may because of network traffics and conflicts. So it's better to find a best way for communicating with multiple Zigbee nodes in same time.

Table 4-7 Test-Communicate with multiple Zigbee units in same time

No of Nodes Request	Received (within 3 min time out)
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	8
10	9
10	5
10	4
10	9
10	10
15	9
15	6
15	5
15	6
15	5
75	10
90	10



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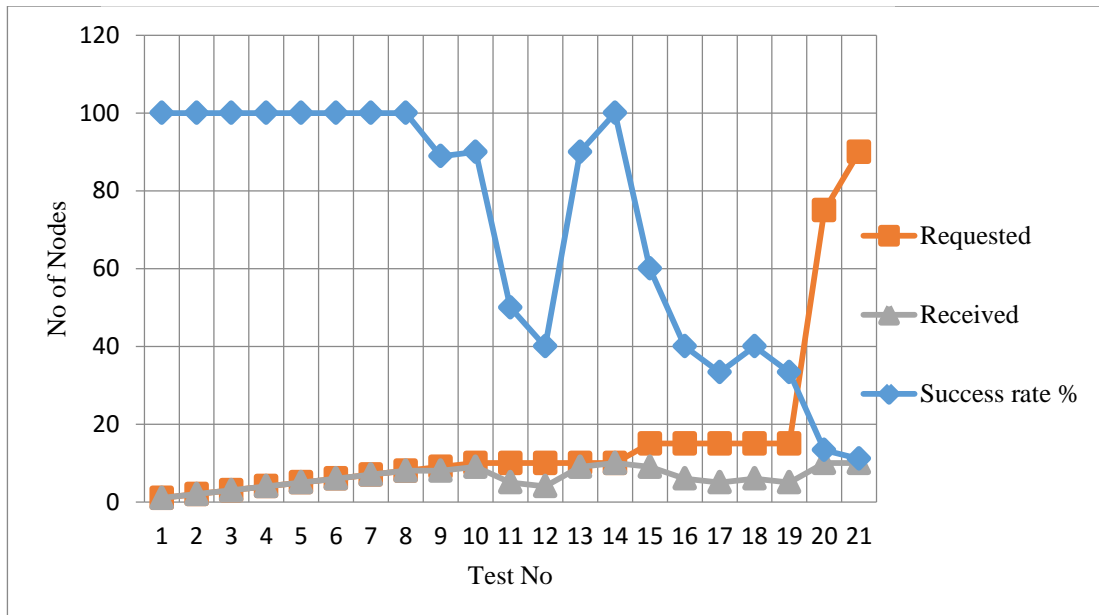


Figure 4-22 Received No of Nodes Vs Test No

So in this research, it is also tried to generate simulation model for describing what happen when requesting data from multiple nodes. For that simple zigbee network was used as in figure 4-23. C is the coordinator and others are the meter end routers.

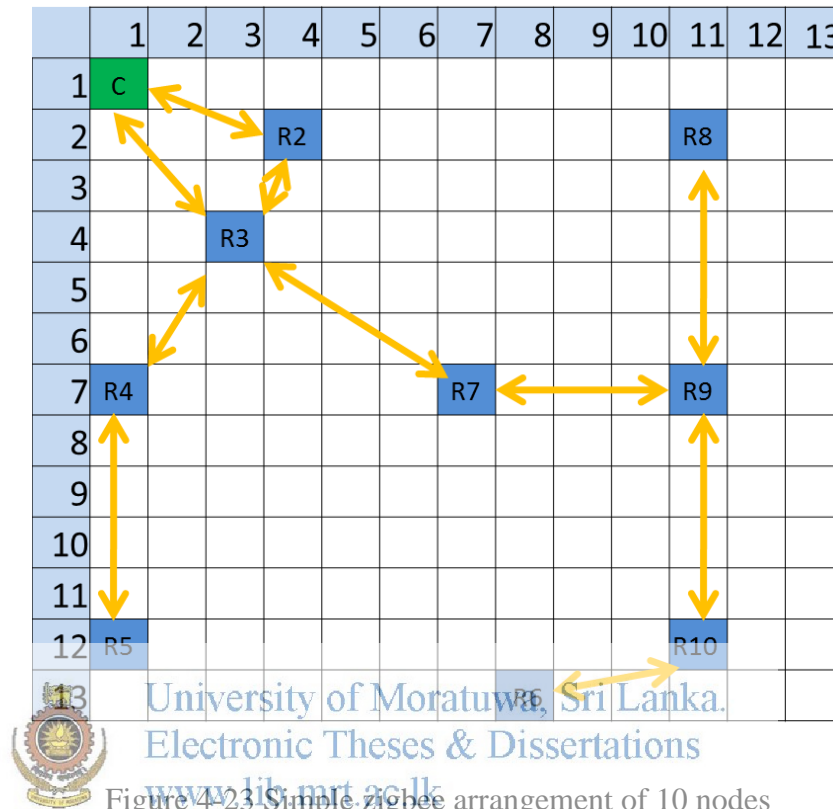


Figure 4-23 Simple zigbee arrangement of 10 nodes

Simulation was created using Matlab Simulink software. For creating simulation, it is used following assumptions,

- Data propagate through network in the forward direction to the coordinator.
- When some link is busy it will send data to secondly optimized node

As this way simulation model was created as per the figure 4-23.

When we input the coordinates of nodes and the targets to the simulation model, then it will generate propagation path. The simulation code is attached in the Appendix E. If it starts with R4, R9, R5, then output of the simulation is shown in the figure 4-25. It was taken 7 steps to propagate all the data to coordinator. In initial step, node 4 will send data to node 3, but node 5 can't send data to node 4 because it is busy in that situation.

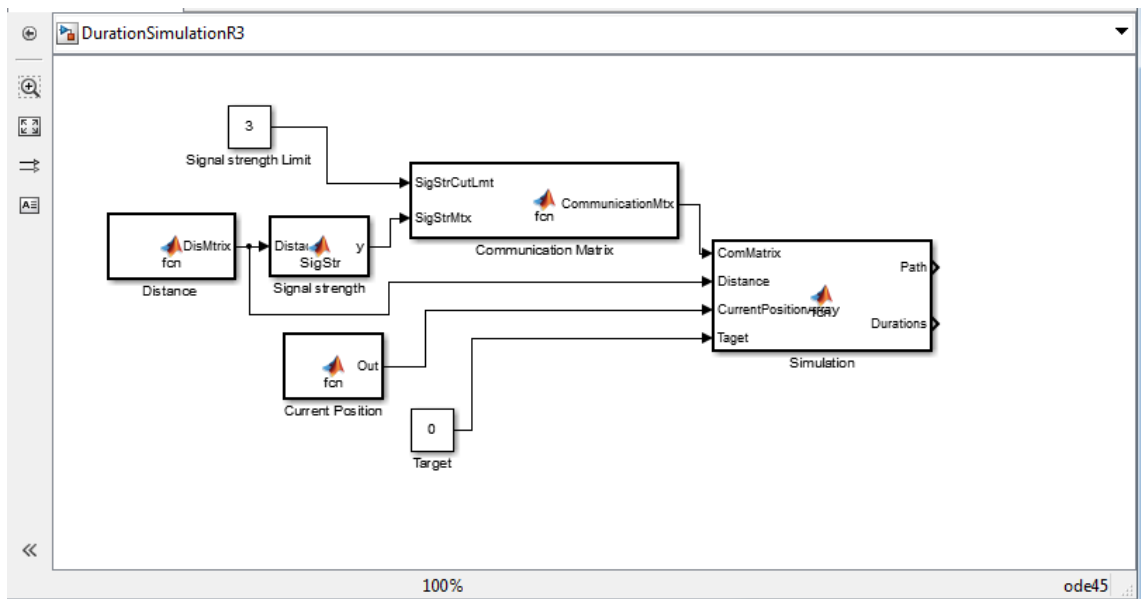


Figure 4-24 Simulation of communication delay

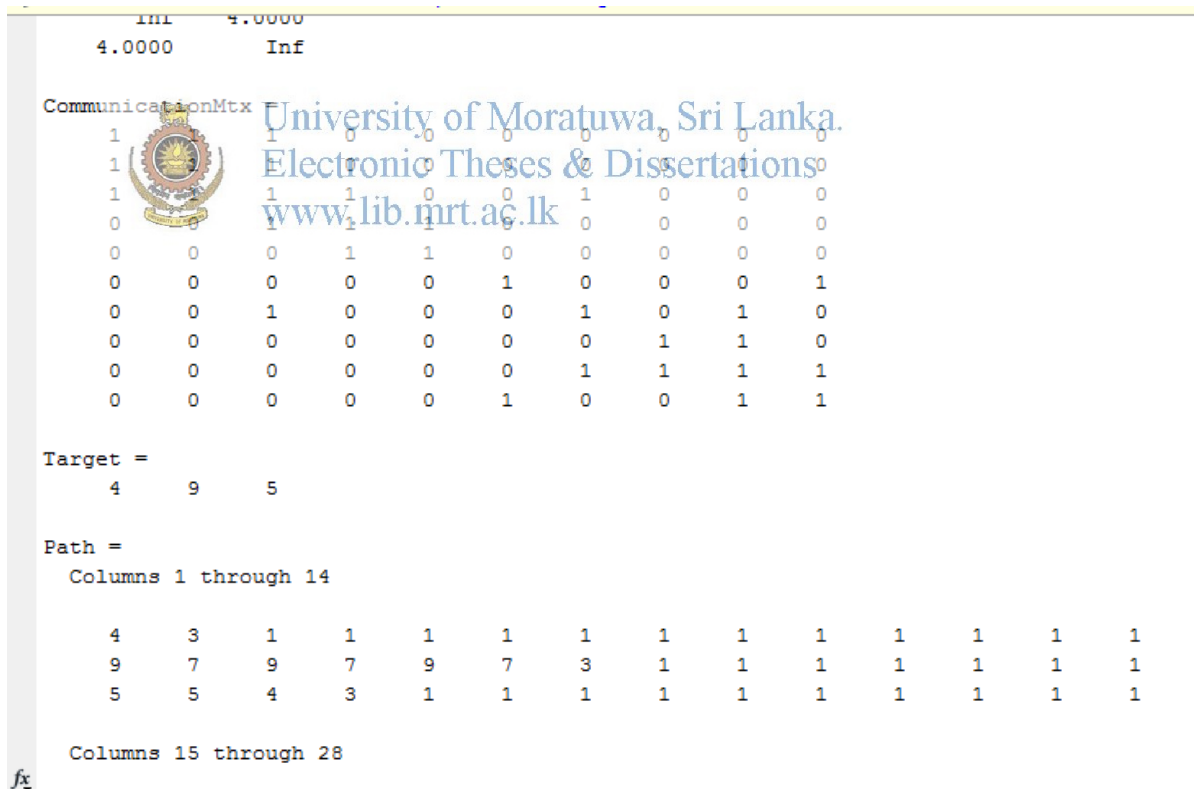


Figure 4-25 Data propagation path



In the simulated data, R2 and R3 are connected directly to the coordinator. So R2 and R3 can be considered as level 2 nodes. R4 and R7 nodes can be considered as level 3 nodes because they are connected to the R3. Like that all the nodes can be categorized to levels. Those levels can be considered for creating groups for polling data to optimize the total communication time.

Then software was developed to generate levels when input Zigbee modules GPS locations as in figure 4-26.

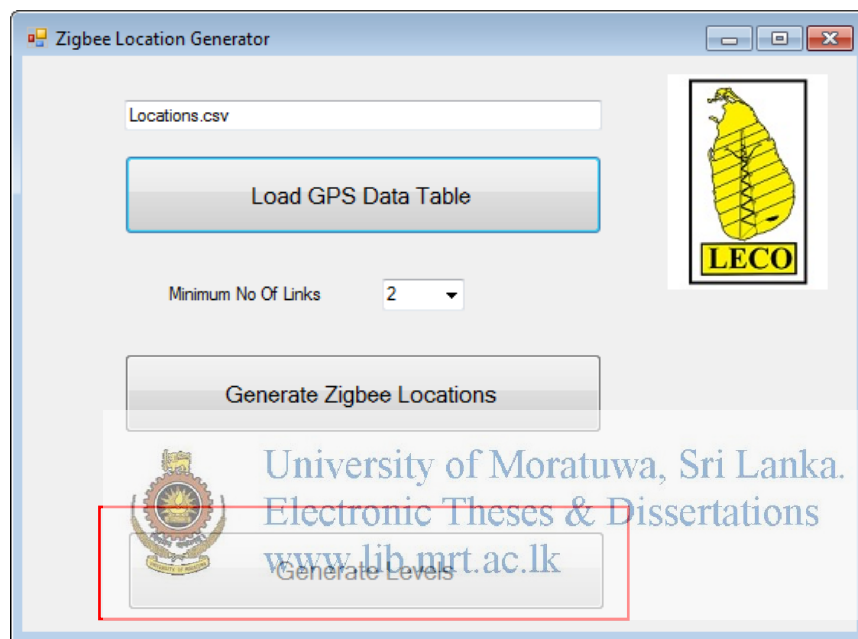


Figure 4-26 Developed software for generating levels

So actual GPS positions were input to the software and generate levels as per the figure 4-27. There are 7 levels in the actual zigbee radio island.

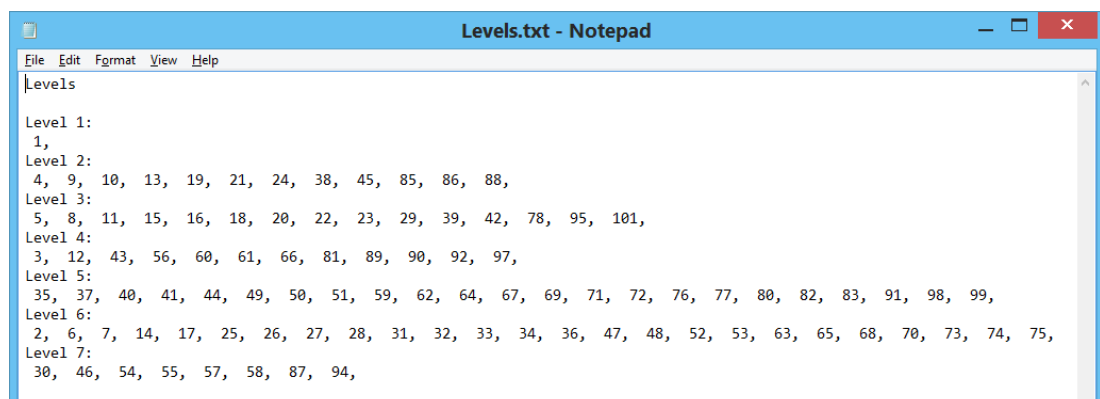


Figure 4-27 Generated Levels

After that some practical tests were carried out considering those levels as per the table 4-10.

Table 4-8 Practical tests with considering levels

Test	Result Within 3 min
Choose 3 nodes from each level and send data 85,86,88,78,95,101,90,92,97,91,98,99,93,96,100,58,87,94	Received all
Choose all nodes in level 6 and send data	Received only 4
Choose all nodes in level 2 and send data	Received only 3
Choose all nodes in level 2 and send data with 10 ms delay	Received all

That implies node selection criteria can be done using the levels. The optimized groups can be generated using communication delay simulation. Thus those functions can be incorporated to the application layer of the Zigbee network as in figure 4-28. Network layer is handled by the Zigbee protocol.

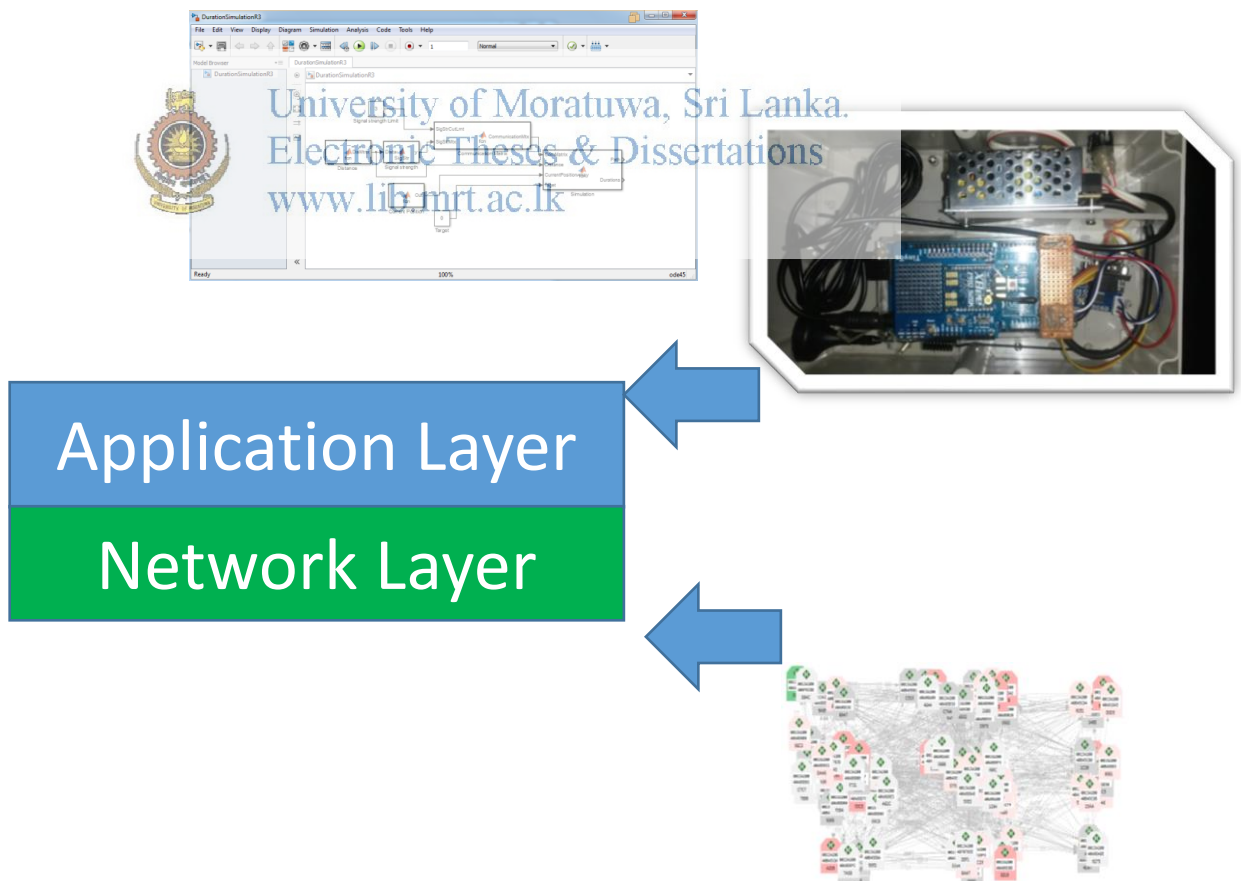


Figure 4-28 Application and Network layers in Zigbee network

#### 4.8. Economic Analysis

By a developed software in figure 4-25, can be optimized the Zigbee pro usage by replacing them by Zigbee (1 mW) units. For that GPS coordinates and minimum number of links, are used as the inputs to the software. The software is generated a report like in figure 4-30 and flow chart is shown in figure 4-31. In that it is used only GPS coordinates of 21 nodes to generate the report.

As per the submitted locations, only 5 number of zigbee pro units are necessary for installing total 21 number of zigbee units. By that total installation cost can be reduced as remaining network with required reliability.

For the software development Visual Studio C# is used.

#### 4.9. Visual Studio C#

Microsoft Visual C# is a product form Microsoft company. Many languages like C, C++, C# etc can be used with Visual studio. By the software it can be developed executable files with forms and many interfaces to serial port, internet and socket applications. Microsoft Visual Studio support many programming languages.

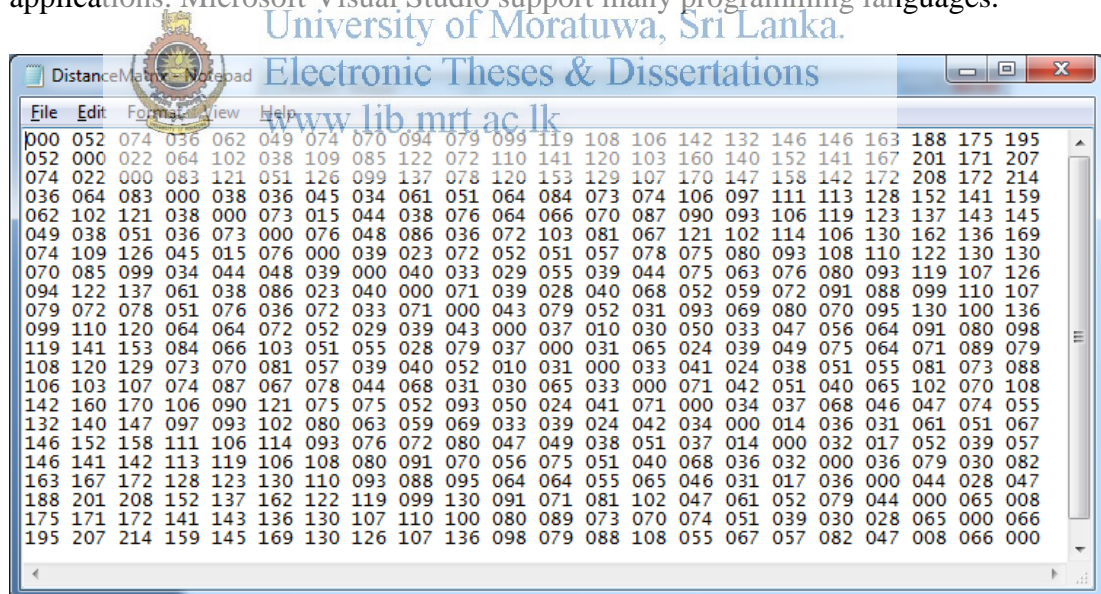


Figure 4-29 Distance Matrix

```
Output - Notepad
File Edit Format View Help
Coordinates
0099098.22 0220271.02
0099116.60 0220222.45
0099125.79 0220202.56
0099131.02 0220285.13
0099132.26 0220323.28
0099142.48 0220250.74
0099146.27 0220327.13
0099164.53 0220293.21
0099168.71 0220332.78
0099176.65 0220262.09
0099192.23 0220302.15
0099195.88 0220338.98
0099200.13 0220308.14
0099204.59 0220275.05
0099219.20 0220344.78
0099224.27 0220311.65
0099237.91 0220313.34
0099244.07 0220281.53
0099255.15 0220315.32
0099264.46 0220357.97
0099271.82 0220293.22
0099272.39 0220358.77
output
0 ZigbeePro
1 Zigbee
2 Zigbee
3 ZigbeePro
4 Zigbee
5 ZigbeePro
6 Zigbee
7 Zigbee
8 Zigbee
9 ZigbeePro
10 Zigbee
11 Zigbee
12 Zigbee
13 Zigbee
14 Zigbee
15 Zigbee
16 Zigbee
17 ZigbeePro
18 Zigbee
19 Zigbee
20 Zigbee
21 Zigbee

No of Zigbee Pro Units = 5
No of Zigbee Units = 17
```

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Figure 4-30 Report

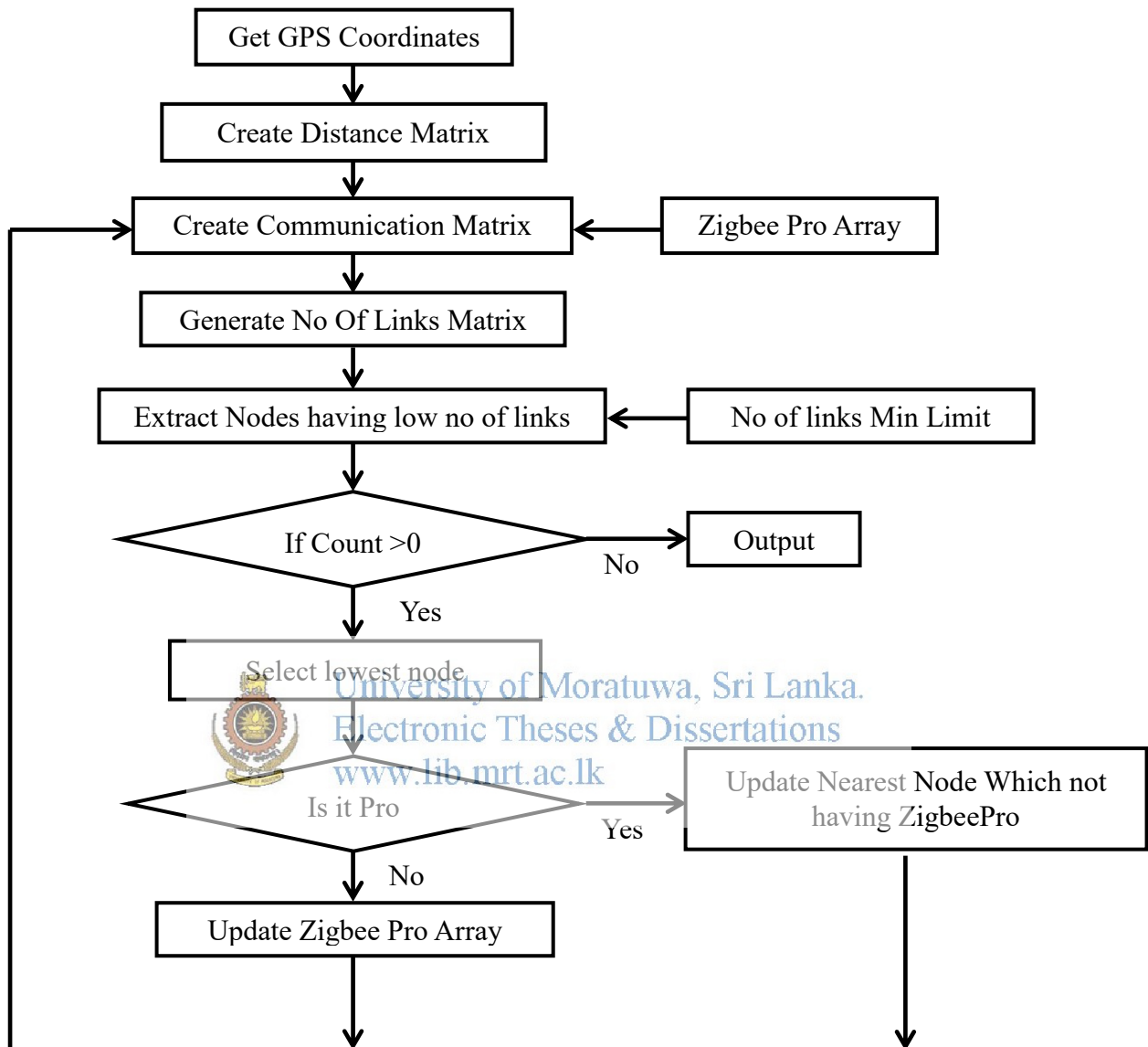


Figure 4-31 Flow chart

Installation cost can be optimized by the software as in table 4-11.

Table 4-9 Cost comparison

Capital Cost		Zigbee (63 mW)			Zigbee (1 mW)		
Meter side		USD	Qty	Total	USD	Qty	Total
	RF Module	55.00	200	11,000.00	35.00	200	7,000.00
	PCB	3.00	200	600.00	3.00	200	600.00
	Enclosure	4.00	200	800.00	4.00	200	800.00
	Controller	-		-	-	-	-
Coordinator Side							
	RF Module	55.00	1	55.00	35.00	1	35.00
	PCB	5.00	1	5.00	5.00	1	5.00
	Controller	30.00	1	30.00	30.00	1	30.00
	Memory	20.00	1	20.00	20.00	1	20.00
	GPRS Modem	100.00	1	100.00	100.00	1	100.00
<b>Grand Total (USD)</b>				<b>12,610.00</b>			<b>8,590.00</b>

In the cost comparison, 200 number zigbee installation is considered. If Zigbee pro modules are used the total cost will be USD 12,610.00. And it can be reduce up to USD 8,590.00 by using zigbee (1 mW) modules. As per the output of the software, the installation cost can be reduced in between those values. Total installation cost reduction with respect to the quantity, is shown in figure 4-32.

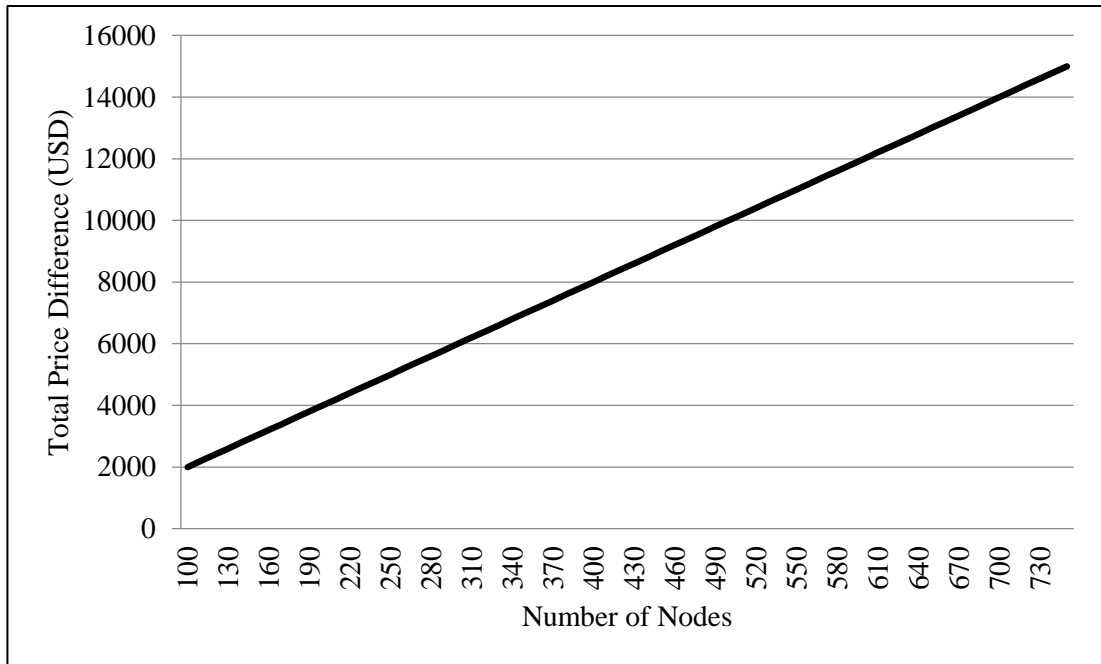


Figure 4-32 Cost reduction vs Number of nodes (between 1 mW and 63 mW)



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### 5. CONCLUSION AND DISCUSSION

In electrical utility various remote nodes are connected to the central server through several methods like PLC, Fiber optics, GPRS and Short range radio frequency network. In Sri Lanka LECO has 0.5 million consumers and CEB have 5 million consumers. Electricity energy meters are installed in every consumer premises. So there should be around 5 million links are necessary for interfacing all meters. But meters are used small amount of data for reading meters. A coordinator based RF technology was studied in the research.

Initially study was carried out using 100 number of zigbee radio island. By the initial tests, communication distances and LQI levels of Zigbee and Zigbee pro were measured. As per the results, it was identified that Zigbee (1 mW) module can communicate up to about 30 m distance while Zigbee pro can communicate up to about 190 m in tested area.

By using Zigbee Radio Island, the parameters like LQI, RSSI and Communication delay were logged.



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By studying LQI variation, it was identified that, there were many links between each and every nodes.

By studying communication delay, it was identified that the delay is varies respect to the day time or night time for some nodes. It can be happened by obstruct to the communication links and changes of weather condition and number of routings.

Some variations of RSSI were observed by the collected data.

According to the above observations, a Simulink simulation model was developed for simulating zigbee Radio Island with respect to the variation of noise level. By that it was identified that number of routing requirement will be increased with respect to the increment of noise level.



So it was identified that installed RMR Radio Island is stable and can be considered as reliable link for meter reading. But it consumed around 150 min to read all meters from server. It will be increased when communication failures occurs.

So another study was carried out for reading multiple meters in same time. Without any simulation or calculation, probability of reading multiple meters was practically measured. It observed that around 8 meters can be communicated in same time. But that value was varying according to the testing group selection.

Thus another simulation model was developed to identify phenomena of routing protocol. A simple model was generated and communication delay was calculated. By that, it was observed various combinations consume various delay times. So this model was testing in practically. It was identified that, there are some relationship between developed model and the real situation. So that model can be used to generate reading meter number combinations in coordinator. Like that systems, central RMR server utilization can be reduced and save some amount of money also.

In addition to that, economical study was carried out between zigbee pro and zigbee (1 mW) models. It was identified that considerable material cost can be reduced by using those two modules in a optimize way. So optimization software is also developed as an outcome of the research. The software is based on GPS coordinates and required number of links.



### 6. FUTURE DEVELOPMENTS

The coordinator functions can be developed further testing them practically. In addition to that better optimization can be obtained if we use data packet sizes for the simulation. So it is required to find other parameters which are affected to the communication speed.

The cost optimization software can be developed further with the inputs of environmental conditions.



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## APPENDIX A : Meter Readout data

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## APPENDIX B : Some Photos



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## APPENDIX C : Coordinator Program

```
//Zigbee side
//Sending Data
byte StartDelimiter = 0x7E;
byte Length[2];
byte FrameDataTXReq[150];//over estimated
byte SizeOfFrameDataTXReq=0;
byte APIFrame[200];//over estimated
byte SizeOfAPIFrame=0;
byte FrameData[150];//over estimated
byte SizeOfFrameData=0;

//Receiving Data
byte ReceAdd[8];
byte ReceData[100];
byte SizeOfReceData;
//Others
byte FrameID=1;

//Modem side

#include <SoftwareSerial.h>

SoftwareSerial ModemSerial(50, 52); // RX, TX

void setup()
{
  Serial.begin(9600);//for Zigbee side communication
```



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```
ModemSerial.begin(9600);//For modem side communication

}

void loop()
{
  delay(100);
  //reading modem side
  //Serial.write(55);
  if (ModemSerial.available())
  {
    }
    GetAPIFrameTXReq(DesAdd, RFData,SizeOfRFData);
    Serial.write(APIFrame, SizeOfAPIFrame);
  }

}
}
}
}
}
}

int GetFrameDataTXReq(byte FrmID, byte DesAdd[], byte RFData[],byte SizeOfRFSData)
{
  int Success=0;
  int i;
  SizeOfFrameDataTXReq=0;
  byte tempFrameDataTXReq[1 + 1 + 8 + 2 + 1 + 1 + SizeOfRFSData];//Length of
frameType FrameID 64DesAdd 16DesAdd BrodRadius Option RFData
  tempFrameDataTXReq[0]=0x10;//frameType
  tempFrameDataTXReq[1]=FrmID;//FrameID
  for(i=0;i<8;i++)//64DesAdd
```



```

{
    tempFrameDataTXReq[2+i]=DesAdd[i];
}
tempFrameDataTXReq[10]=0xFF;//16DesAdd
tempFrameDataTXReq[11]=0xFE;//16DesAdd
tempFrameDataTXReq[12]=0;//BrodRadius
tempFrameDataTXReq[13]=0;//Option
for(i=0;i<SizeOfRFSDData;i++)//RFData
{
    tempFrameDataTXReq[14+i]=RFData[i];
}

SizeOfFrameDataTXReq=sizeof(tempFrameDataTXReq);
for(i=0;i<SizeOfFrameDataTXReq;i++)
{
    FrameDataTXReq[i]= tempFrameDataTXReq[i];
}

```



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```

Success=1;
return Success;
}
byte GetChecksum()//done
{
    unsigned long ChkSumLong=0xFF;
    byte ChkSum=0;
    //Serial.write(SizeOfFrameData);
    for(int i=0;i<SizeOfFrameData;i++)
    {
        ChkSumLong -= FrameData[i];
        //Serial.write(FrameData[i]);
    }
}

```

```

}
//Serial.write('A');
ChkSum=ChkSumLong;
return ChkSum;
}
byte GetChecksum(byte Data[],byte SizeOfData)//for modem side
{
    unsigned long ChkSumLong=0xFF;
    byte ChkSum=0;
    //Serial.write(SizeOfFrameData);
    for(int i=0;i<SizeOfData;i++)
    {
        ChkSumLong -= Data[i];
        //Serial.write(FrameData[i]);
    }
    //Serial.write('A');
    ChkSum=ChkSumLong;
    return ChkSum;
}
unsigned int GetLength()//done
{
    unsigned int Length=SizeOfFrameData;
    return Length;
}

int GetAPIFrameTXReq(byte DesAdd[], byte RFData[],byte SizeOfRFData)
{
    int Success=0;
    SizeOfAPIFrame=0;
    int i;
    // FrameDataTXReq={0,0};//Initialize the FrameDataTXReq
    //Serial.write(1);
    GetFrameDataTXReq(FrameID, DesAdd, RFData,SizeOfRFData);
    //Serial.write(FrameDataTXReq, SizeOfFrameDataTXReq);

```



```

SizeOfFrameData=SizeOfFrameDataTXReq;
for(i=0;i<SizeOfFrameData;i++)
{
    FrameData[i]=FrameDataTXReq[i];
}

byte CheckSum = GetCheckSum();
// Serial.write(2);Serial.write(CheckSum);
unsigned int tempLength = GetLength();
//Serial.write(3);
    Length[0]=tempLength;
    Length[1]=tempLength >> 8 ;
// Serial.write(4);
    byte tempAPIFrame[1+2+SizeOfFrameDataTXReq + 1];//length of StartDelimiter length
    FrameData CheckSum
// Serial.write(5);
    tempAPIFrame[0]=StartDelimiter;//StartDelimiter
// Serial.write(6);
    tempAPIFrame[1]=Length[1];//length
    tempAPIFrame[2]=Length[0];//length
// Serial.write(7);
for(i=0;i<SizeOfFrameData;i++)
{
    tempAPIFrame[i+3]=FrameData[i];
}
tempAPIFrame[SizeOfFrameDataTXReq+2+1]=CheckSum;

SizeOfAPIFrame=sizeof(tempAPIFrame);
for(i=0;i<SizeOfAPIFrame;i++)
{

```



```

    APIFrame[i]=tempAPIFrame[i];
}
//Serial.write(APIFrame, SizeOfAPIFrame);

```

```

    FrameID ++;
    Success=1;
    return Success;
}

```

*boolean CheckCheckSum(char bufferWithCSum[], byte SizeOfbufferWithCSum)//Checking checksum for receiving data*

```

{
    boolean Success=false;
    int IntSum=0;
    byte Sum=0;
    for(int i=0; i<SizeOfbufferWithCSum; i++)
    {
        IntSum += (byte)bufferWithCSum[i];
    }
    Sum=IntSum;
    if(Sum == 0xFF)
        Success=true;
    return Success;
}

```

*boolean CheckCheckSum(char buffer1[], byte SizeOfbuffer1, char buffer2WithCSum[], byte SizeOfbuffer2WithCSum)//Checking checksum for receiving data*

```

{
    boolean Success=false;
    int IntSum=0;
    byte Sum=0;
    for(int i=0; i<SizeOfbuffer1; i++)

```

```

{
    IntSum +=(byte)buffer1[i];
}
for(int i=0;i<SizeOfbuffer2WithCSum;i++)
{
    IntSum +=(byte)buffer2WithCSum[i];
}
Sum=IntSum;
if(Sum == 0xFF)
    Success=true;
return Success;
}

void serialEvent() //for zigbee side serial
{
    if(Serial.available())
    {
        if (Serial.read() == 0x7E) //checking Start delimiter
        {
            char bufferLen[2]; //reading length
            Serial.setTimeout(1000);
            if(Serial.readBytes(bufferLen, 2)!=0)
            {
                int length= (((int)bufferLen[0]) << 8) + (int)bufferLen[1];
                char bufferData[length+1];
                Serial.setTimeout(1000);
                if(Serial.readBytes(bufferData, length + 1)!=0)//Reading Frame data +1 for
checksum
                {
                    if(bufferData[0] == (char)0x90)//Receive Packet
                    {
                        if(CheckChecksum(bufferData, length + 1)==true)//error in checksum
                        {

```



```

for(int i=0;i<8;i++)
{
    ReceAdd[i]=bufferData[i+1];
}
SizeOfReceData=length-12;
for(int i=0;i<SizeOfReceData;i++)
{
    ReceData[i]=bufferData[i+12];
}

//arrange data for sending to modem
byte ReceAddAndData[8+SizeOfReceData];

for(int i=0;i<8;i++)
{
    ReceAddAndData[i]=(byte)ReceAdd[i];
}

for(int i=8;i<sizeof(ReceAddAndData);i++)
{
    ReceAddAndData[i]=(byte)ReceData[i-8];
}

//Sending data to modem
ModemSerial.write(0x7E);//start delimiter
int LengthReceAddAndData=sizeof(ReceAddAndData);
byte Length[2];
Length[0]=LengthReceAddAndData;
Length[1]=LengthReceAddAndData >> 8 ;
for(int i=0;i<8;i++)
{
    ModemSerial.write(ReceAddAndData[i]);//length
}
ModemSerial.write(Length[1]);

```





```
ModemSerial.write(Length[0]);
for(int i=8;i<sizeof(ReceAddAndData);i++)
{
    ModemSerial.write(ReceAddAndData[i]);//length
}

ModemSerial.write(GetChecksum(ReceAddAndData,sizeof(ReceAddAndData)));//check sum
}
}
}
}

}
}
}
```



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## APPENDIX D : LQI Variation



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## APPENDIX E : Simulation Program-Communication Speed

### Function Distance Matrix

```
function DisMtrix = fcn()
%#codegen
L=[1 2;%Locations
   2 3;
   4 5;
   5 6;
   1 2;
   2 3;
   4 5;
   5 6;
   4 5;
   5 6
  ];
m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10

        m(r,c) = (sqrt((L(r,1)-L(c,1))^2 + (L(r,2)-L(c,2))^2));
    end;

end;
DisMtrix=m
```

### Function Signal Strength

```
function y = SigStr(Distace)
%#codegen

m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10

        m(r,c) = 1/(Distace(r,c))^2;
    end;

end;
y=m
```

### Function Modify Noise

```
function xx = fcn(u)
%#codegen
mm= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10
        if c<r
```

```

        mm(r,c) = u(r,c);
        mm(c,r) = u(r,c);
    end ;

end;

end;
xx = mm;

Function Communication Matrix

function CommunicationMtx = fcn(SigStrCutLmt,SigStrMtx)
%#codegen
m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10
        if SigStrMtx(r,c)>SigStrCutLmt

            m(r,c)=1;

        else

            m(r,c)=0;
        end;
    end;
end;

end;
CommunicationMtx=m

Function Communication Speed

function ComSpeed = ComSp(SS,RN)
%#codegen

m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        m(r,c) =9600*log2(1+(SS(r,c)/ RN(r,c)));

    end;

end;

end;
ComSpeed=m;

Function Communication links

```



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```
function SpeedsOfLinks = fcn(ComMatrix,ComSpeed)
%#codegen
```

```
m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        if ComMatrix(r,c)==1
            m(r,c)=ComSpeed(r,c)
        end
    end;
end;
```

```
end;
```

```
SpeedsOfLinks =m;
```

Function Low Speed Links

```
function LowSpeedLinks = fcn(SpeedsOfLinks,SpeedRef)
%#codegen
```

```
m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10
        if SpeedsOfLinks(r,c)<SpeedRef
            m(r,c)=10
        else
            m(r,c)=0;
        end;
    end;
end;
```

```
end;
```

```
LowSpeedLinks = m;
```

Function Reroute

```
function NewComSpeed = fcn(ComSpeed,LowSpeedLinks,ComMatrix)
%#codegen
```

```
m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10
        if LowSpeedLinks(r,c)==1
            for cc = 1:10;
                if ComMatrix(r,cc)==1
                    ComSpeed(r,cc)=ComSpeed(r,cc)*98/100
                end;
            end;
        end;
    end;
end;
```

```
end;

for rr=1:10;
    if ComMatrix(rr,c)==1
        ComSpeed(rr,c)=ComSpeed(r,cc)*98/100
    end;
end;
end;
end;

end;

NewComSpeed = ComSpeed;
```



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## APPENDIX F : Simulation Program-Communication Path

Function Distance Matrix

```
function DisMtrix = fcn()
%#codegen
L=[1 1;%Locations
  2 4;
  4 3;
  7 1;
  12 1;
  13 8;
  7 7;
  2 11;
  7 11;
  12 11
  ];
m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10

        m(r,c) = (sqrt((L(r,1)-L(c,1))^2 + (L(r,2)-L(c,2))^2));
    end;

end;
DisMtrix=m
```

Function Signal Strength

```
function y = SigStr(Distance)
%#codegen

m= zeros(10,10);
for r = 1:10;

    for c=1:10;
        % m(r,c)=10

        m(r,c) = 100/(Distance(r,c))^2;
    end;

end;
y=m
```

Function Communication Matrix

```
function CommunicationMtx = fcn(SigStrCutLmt,SigStrMtx)
%#codegen
m= zeros(10,10);
for r = 1:10;
```

```

for c=1:10;
    % m(r,c)=10
    if SigStrMtx(r,c)>SigStrCutLmt

        m(r,c)=1;

    else

        m(r,c)=0;

    end;
end;

end;
CommunicationMtx=m

```

#### Function Current Position

```

function Out = fcn()
%#codegen
Target=[4 9 5 ]

```

```

Out = Target;

```



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#### Function Simulation

```

function [Path,Durations]=
fcn(ComMatrix,Distance,CurrentPositionArray,Taget)
%#codegen
ComMatrixSize=[10 10];
DistanceMatrixSize=ComMatrixSize;
CurrentPositionSize=3;
CurrentPositionHistory = zeros(CurrentPositionSize,100);
OccupiedNodes=[0 0 0 0 0 0 0 0 0 0];
for i=1:CurrentPositionSize;
    CurrentPositionHistory(i,1)=CurrentPositionArray(i);

end;

for Time=2:100;
for i=1:CurrentPositionSize;
    if CurrentPositionArray(i)==1
    else
        OccupiedNodes(CurrentPositionArray(i))=1;
    end;

end;

end;

```



```

for CurrentPositionIndex = 1:CurrentPositionSize;

CurrentPositionHistory(CurrentPositionIndex,Time)=CurrentPositionArray(CurrentPositionIndex);

SelectedCurrentPosition=CurrentPositionArray(CurrentPositionIndex);
if SelectedCurrentPosition == 1

else

SelectedLowestDistance=1000;%Temp value only
SelectedNode=0;
for ComIndex=1:ComMatrixSize(2);
    if ComMatrix(SelectedCurrentPosition,ComIndex)==1
        if Distance(ComIndex,1) < SelectedLowestDistance
            if OccupiedNodes(ComIndex) == 0
                SelectedLowestDistance=Distance(ComIndex,1);
                SelectedNode=ComIndex;
            end;
        end;
    end;
end;

end;
if SelectedNode > 0

CurrentPositionHistory(CurrentPositionIndex,Time)=SelectedNode;
CurrentPositionArray(CurrentPositionIndex)=SelectedNode;
OccupiedNodes(SelectedNode)=1;

end;
end ;

% ComMatrix
%Path=1;
%for c=1:10;
    % m(r,c)=10

    % m(r,c) = (sqrt((L(r,1)-L(c,1))^2 + (L(r,2)-L(c,2))^2));
%end;

end;
OccupiedNodes=[0 0 0 0 0 0 0 0 0 0];
end;
%Path = Target;
Path=CurrentPositionHistory
Durations=2;

```



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## APPENDIX G : Program-VS-Finding Levels and Zigbee pro selection

```
public bool[] IsZigbeePro;
    public int[] NoOfComLinks;
    public int NoOfLinkMinLimit;
    public NetworkData()
    {
        IsZigbeePro = new bool[Coordinates.GetLength(0)];
        for (int i = 0; i < IsZigbeePro.Length; i++)
        {
            IsZigbeePro[i] = true;
        }

        CommunicationMatrix = new
bool[CommunicationMatrixInt.GetLength(0),
CommunicationMatrixInt.GetLength(0)];
        for (int r = 0; r < CommunicationMatrixInt.GetLength(0);
r++)
        {
            for (int c = 0; c <
CommunicationMatrixInt.GetLength(0); c++)
            {
                CommunicationMatrix[r, c] =
CommunicationMatrixInt[r, c] == 1 ? true : false;
            }
        }
    }
    public NetworkData(bool IsAllZigbeePro, int NodeCount)
    {
        IsZigbeePro = new bool[NodeCount];
        for (int i = 0; i < IsZigbeePro.Length; i++)
        {
            IsZigbeePro[i] = IsAllZigbeePro;
        }
        NoOfComLinks = new int[NodeCount];

        CommunicationMatrix = new
bool[CommunicationMatrixInt.GetLength(0),
CommunicationMatrixInt.GetLength(0)];
        for (int r = 0; r < CommunicationMatrixInt.GetLength(0);
r++)
        {
            for (int c = 0; c <
CommunicationMatrixInt.GetLength(0); c++)
            {
                CommunicationMatrix[r, c] =
CommunicationMatrixInt[r, c] == 1 ? true : false;
            }
        }
    }
    public double[,] GetDistanceMatrix(double[,] Codints)
    {
        int CoordinatesLength = Codints.GetLength(0);
        double[,] DistanceMatrix = new double[CoordinatesLength,
CoordinatesLength];
        for (int r = 0; r < CoordinatesLength; r++)
        {
            for (int c = 0; c < CoordinatesLength; c++)
```



```

        {
            DistanceMatrix[r, c] =
Math.Sqrt(Math.Pow((Codints[r, 0] - Codints[c, 0]), 2) +
Math.Pow((Codints[r, 1] - Codints[c, 1]), 2));
        }
    }
    return DistanceMatrix;
}
public bool[,] GetCommunicationMatrix(double[,]
DistanceMatrix, bool[] IsZigbeePro)
{
    int Count=IsZigbeePro.Length;
    bool[,] ComMatrix = new bool[Count, Count];
    for (int r = 0; r < Count; r++)
    {
        for (int c = 0; c < Count; c++)
        {
            if(IsZigbeePro[r] & IsZigbeePro[c])
            {
                if(DistanceMatrix[r, c]<ZigbeeProComDis)
                {
                    ComMatrix[r, c]=true;
                }
                else
                {
                    ComMatrix[r, c]=false;
                }
            }
            else
            {
                if(DistanceMatrix[r, c]<ZigbeeComDis)
                {
                    ComMatrix[r, c]=true;
                }
                else
                {
                    ComMatrix[r, c]=false;
                }
            }
        }
    }
    return ComMatrix;
}
public int UpdateNoOfLinks()
{
    int MinNoOfLinks = Coordinates.GetLength(0);
    for (int r = 0; r < Coordinates.GetLength(0); r++)
    {
        int TempNoOfLinks = 0;
        for (int c = 0; c < Coordinates.GetLength(0); c++)
        {
            if (CommunicationMatrix[r, c])
            {
                TempNoOfLinks++;
            }
        }
        NoOfComLinks[r] = TempNoOfLinks;
        if (MinNoOfLinks > TempNoOfLinks)

```



```

        {
            MinNoOfLinks = TempNoOfLinks;
        }
    }
    return MinNoOfLinks;
}
public void UpdateProModule ()
{
    try
    {
        int TempMinNoOfLinks =
Coordinates.GetLength(0); //Temp Value
        int TempMinNoOfLinksIndex=-1;
        bool[] TempIsChecked = new
bool[Coordinates.GetLength(0)];
        for (int rr = 0; rr < Coordinates.GetLength(0);
rr++)
        {
            TempMinNoOfLinks =
Coordinates.GetLength(0); //Temp Value
            int r = rr;
            for (int tempr = 0; tempr <
Coordinates.GetLength(0); tempr++)
            {
                if ((TempMinNoOfLinks >
NoOfComLinks[tempr]) && (! TempIsChecked[tempr]))
                {
                    TempMinNoOfLinksIndex = tempr;
                    TempMinNoOfLinks = NoOfComLinks[tempr];
                    r = tempr;
                    TempIsChecked[r] = true;

                    if (NoOfComLinks[r] < NoOfLinkMinLimit)
                    {
                        if (!IsZigbeePro[r])
                        {
                            IsZigbeePro[r] = true;
                            break;
                        }
                        else
                        {
                            double tempDisMin = 5000; //temp max
value
                            int tempDisMinIndex = -1;
                            for (int c = 0; c <
Coordinates.GetLength(0); c++)
                            {
                                if ((tempDisMin > DistanceMatrix[r,
c]) && (!IsZigbeePro[c]))
                                {
                                    tempDisMin = DistanceMatrix[r,
c];
                                    tempDisMinIndex = c;
                                }
                            }
                            if (tempDisMin <= ZigbeeProComDis)

```



```

        {
            IsZigbeePro[tempDisMinIndex] = true;
            break;
        }
    }
}

catch
{
}
}

public class NetworkCombinations
{
    bool[] OccupiedList;
    bool[,] ComMatrix;
    public NetworkCombinations(bool[,] CommunicationMatrix)
    {
        bool[] OccupiedList=new
bool[CommunicationMatrix.GetLength(0)];
        ComMatrix = CommunicationMatrix;
    }
    public bool[] GetCombinations(bool[] ParentCombinations,ref
bool[] OccupiedList,bool[,] CommunicationMatrix)
    {
        bool[] ChildList=new
bool[CommunicationMatrix.GetLength(0)];
        for (int i = 0; i < ParentCombinations.GetLength(0);
i++)
        {
            if (ParentCombinations[i])
            {
                int r = i;
                for (int c = 0; c <
CommunicationMatrix.GetLength(1); c++)
                {
                    if (CommunicationMatrix[r, c] == true)
                    {
                        if (!OccupiedList[c])
                        {
                            ChildList[c] = true;
                            OccupiedList[c] = true;
                        }
                    }
                }
            }
        }
        return ChildList;
    }
}
}

```

```

public ArrayList GetCombinationsInLevels ()
{
    bool[] ChildList;
    bool[] ParentCombinations=new
bool[ComMatrix.GetLength(0)];
    ParentCombinations[1]=true;
    OccupiedList=new bool[ComMatrix.GetLength(0)];
    ArrayList Levels = new ArrayList();
    Levels.Add(ParentCombinations);
    while (OccupiedList.Contains(false))
    {
        ChildList = GetCombinations(ParentCombinations, ref
OccupiedList, ComMatrix);
        ParentCombinations = ChildList;
        Levels.Add(ParentCombinations);
    }
    return Levels;
}
}

```



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**APPENDIX H : BZ 501 Transformer area map**



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