WSN Based Power Monitoring for Smart Grids

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Declaration

I declare that this written submission represents my ideas in my own words, and where ideas or words of others have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

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This Thesis entitled WSN Based Power Monitoring for Smart Grids by Alok Kumar Bharati is approved for the degree of Master of Technology from IIT Hyderabad

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To my parents and brother

Nomenclature

Roman Letters

t	:	Time
P	:	Power
P_Source	:	Power of the Source
P_Load	:	Power of the Loads
P_Losses	:	Power loss
R	:	Resistor
v	:	Voltage output of the DAC
V_1	:	Voltage input to ADE 7757
V_2	:	Voltage proportional to load current
V_PN	:	Phase to neutral voltage
I_L	:	Load Current
M	:	Mega

Greek Letters

Ω	:	Ohms
ω	:	Angular frequency in rad/sec
μ	:	Micro
Φ	:	Phase angle between voltage and current

Subscripts

Source	:	Corresponding to source
Load	:	Corresponding to load
Losses	:	Corresponding to losses in the system

Abbreviations

AC	:	Alternating Current
ADC	:	Analog to Digital Converter
ALU	:	Arithmetic Logic Unit
ARIB	:	Association of Radio Industries and Businesses
ARR	:	Accounting Rate of Return
AWGN	:	Additive White Gaussian Noise
CMOS	:	Complementary Metal Oxide Semiconductor
CPU	:	Central Processing Unit
CT	:	Current Transformer
DA	:	Distribution Automation System
DAC	:	Digital to Analog Converter
DC	:	Direct Current
DMA	:	Direct Memory Access

DSSS	:	Digital direct Sequence Spread Spectrum
EEPROM	:	Electrically Erasable Programmable Read Only Memory
ELP	:	Extended Low Power
ETSI	:	European Telecommunication Standards Institute
FCC	:	Federal Communications Commission
GPRS	:	General Packet Radio Service
GSM	:	Global System for Mobile communication
GUI	:	Graphical User Interface
HP	:	High Power
HPF	:	High Pass Filter
I2C	:	Inter IC(integrated circuit) Bus ("I squared C" Bus)
IC	:	Integrated Circuit
IEEE	:	Institute of Electrical and Electronics Engineers
ISM	:	Industrial, Scientific and Medical
ISP	:	In-System Processor
JTAG	:	Joint Test Action Group
LP	:	Low Power
LPF	:	Low Pass Filter
LSB	:	Least Significant Bit
MIPS	:	Millions of Instructions Per Second
MoP	:	Ministry of Power
MSB	:	Most Significant Bit
OQPSK	:	Offset Quadrature Phase Shift Keying
PC	:	Personal Computer
PT	:	Potential Transformer
PWM	:	Power Management
QoS	:	Quality of Service
RF	:	Radio Frequency
RISC	:	Reduced Instruction Set Computer
RSSI	:	Radio frequency (RF) received Signal Strength Indication
RTC	:	Real Time Counter
SCADA	:	Supervisory Control and Data Acquisition System
SERC	:	State Electricity Regulatory Commission
SPI	:	Serial Peripheral Interconnect
SRAM	:	Static Random Access Memory
T&D	:	Transmission and Distribution
UART	:	Universal Asynchronous Receiver/Transmitter
USART	:	Universal Synchronous/Asynchronous Receiver/Transmitter
WiMAX	:	Worldwide Interoperability for Microwave Access
WSN	:	Wireless Sensor Networks

Abstract

Electrical power system consists of vast and complex network of transmission and distribution power lines. Transmission systems are managed by huge substations and are largely stable and operate within the limits. Distribution systems, on the other hand, are largely complex and are often pushed to the limits of its operation (operating voltages and currents). There is no efficient methodology for monitoring the large electrical distribution systems which are often exposed to faults, disturbances and interruptions. Along with efficient monitoring, an in-depth analysis of the behavior of the distribution systems is needed to design a more robust and efficient power system. The upcoming smart grid technology is a promising one to make the power systems more robust and efficient with the distributed energy sources supplying power to the grid. In this work, an efficient power monitoring system based on the wireless sensor network technology is proposed to enhance the functioning of large distribution systems.

Power monitoring system based on the Wireless Sensor Network (WSN) technology is designed and developed, wherein the real power consumed by the load is sensed and is communicated to the base station/central server using the wireless communication technology. The power monitoring module is a sensor which actually senses the current and voltage, computes power at periodic intervals. The system is interfaced with a wireless communication module based on IRIS motes. 802.15.4 protocol is used to establish the wireless communication among the different nodes in the network. The central server is a rich repository of power information, as it collects the data on the real power from various loads being monitored by different nodes at periodic intervals. A Graphical User Interface (GUI) is developed at the server to monitor various parameters like health, configuration etc., of the network. The rich source of data on power consumption at the server can be used for further analysis, based on which a number of applications can be built. One such application which is being discussed in the thesis is the power theft detection. An algorithm for detecting power theft in the distribution system is proposed and tested on a small scale in the lab. Other wireless communication technology like the Global System for Mobile communication (GSM) is also demonstrated for the proposed power monitoring system. Other applications that can be developed on the proposed system are also discussed.

Contents

Chapter 1

Introduction

This chapter talks about the general power systems scenario in India and the issues in it. It also describes how power monitoring can address these issues to improve the functioning of the power systems. It also highlights the contribution made by this thesis in addressing the issues in power systems

1.1 Power System Scenario in India

Electrical power transmission and distribution systems are very complex and cover extensively large geographical areas. The electrical power transmission system is relatively very well planned, designed and managed when compared to its supplementary electrical power distribution network. The electrical power distribution system is a very complex and complicated system to be handled. There are many un-foreseen events occurring in the distribution systems like the faults, over loading, voltage disturbances, uncontrolled load switching, fluctuations in voltages and load currents resulting in systems which are very difficult to handle. The distribution system cannot handle all these events effectively as there are no effective real time monitoring systems in the present electrical power distribution systems. The electrical power distribution system needs a very effective monitoring system. Fig 1.1 shows the general stages involved in transmitting power from the generating station to the loads.

The existing Distribution Automation System (DA) is a control systems which includes real time monitoring of operating parameters like currents, voltages, real power, reactive power, power factor, frequency, etc., at all points of the substation. It also takes care of status of circuit breakers, remote operation of circuit breakers and archiving of historical data, audio alarm for limit violations and breaker tripping, recording of sequence of events and recording of maxima and minima of operating parameters [1]-[6]. This monitoring is done at a substation level; however a cost- effective power monitoring and control system needs to be developed at the distribution level. The present project is an attempt to develop a wireless power monitoring system at the distribution level. The distribution systems have higher losses than the transmission systems. The distribution systems in India have enormously high distribution losses [7].

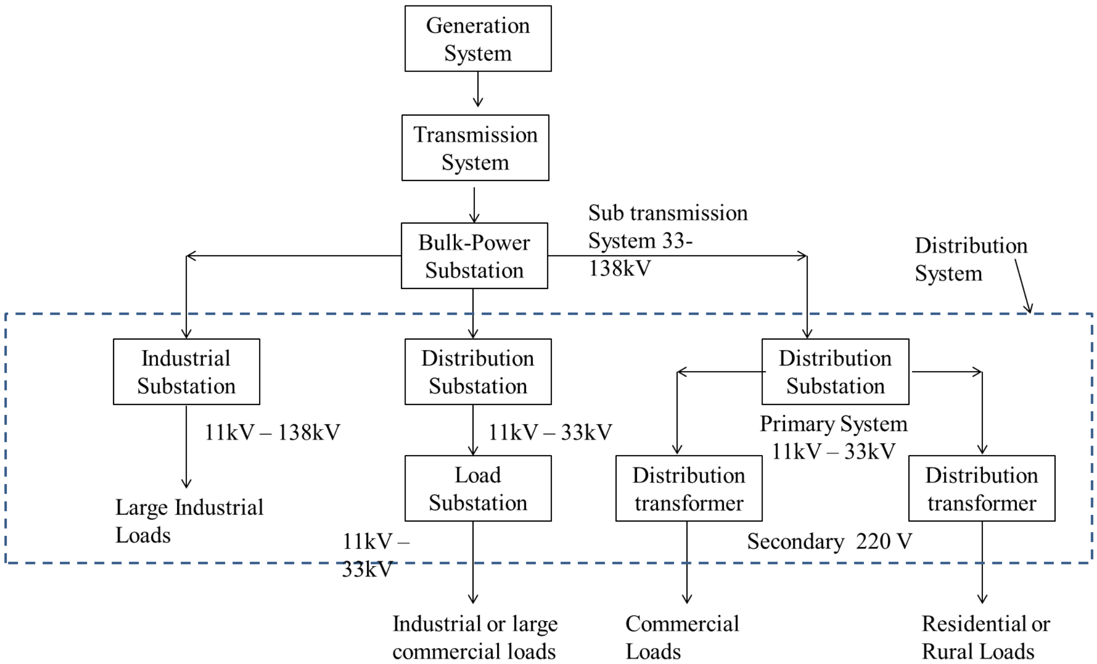

Figure 1.1: Schematic representation of the main stages involved in transmission and distribution network

1.2 Transmission and Distribution (T&D) Losses

T&D losses have been a concern for the Indian electricity sector since these have been very high when compared with other developed countries. The present T&D losses including unaccounted energy are about 30% (As per Ministry of Power (MoP), however this figure is optimistically low) [7] and there is need to reduce these losses through efficient management and the best operation and maintenance practices of the transmission and distribution. When mentioned about T&D losses it also includes the theft of electricity, although it is the part of commercial loss but there is no way to segregate theft from the T&D losses. In practice, the energy billed and the input energy is known. The difference between these two is T&D loss and obviously the theft is included in this loss [7].

State Electricity Regulatory Commissions (SERC) and MoP have also been trying to segregate T&D loss and commercial loss but have been unsuccessful in segregating these losses as theft (the part of commercial loss) is embedded with T&D.

Electricity theft (seen in Fig 1.2) is at the center of focus all over the world but electricity theft in India has a significant effect on the Indian economy, as this figure is considerably high (the loss caused due to theft has not been identified and there is no segregation of loss due to theft and technical losses in the system). The loss on account of theft is reflected in Accounting Rate of Return (ARR) of the electricity companies and it is clear that these costs are routinely passed on to the customers in the form of higher energy charges. The technical and commercial losses can be

Figure 1.2: A photograph showing a person hooking wires to the distribution lines to steal power

reduced significantly if the entire distribution system is monitored effectively. Successful monitoring of a distribution can mean monitoring of the voltages, currents, power factors, harmonics, overloading and temperature of the transformers. These facts force the power engineers to look into the solutions to solve this problem. A power monitoring system can be the first step for solving this issue.

1.3 Importance of A Power Monitoring System

The power monitoring system is a basic module to build a complete distribution monitoring system. The data on the real-time power consumption of loads is required to plot the load and demand curves, which are essential to schedule the generation of power. The power monitoring module can be enhanced easily to monitor the currents, voltages and power factors. The module computes the power from monitored voltages and currents. The general three phase (3-Φ) system monitoring module needs very detailed and precise timing to be maintained. This is needed to compute the powers from each of the three phases simultaneously. The power monitoring module designed and developed measures the real power consumed by the loads on a real time basis for a single phase system. The information of the real power consumed by the loads is computed and the average real power is computed using the designed hardware module. The data on the monitored power at the different loads in the network is stored in a rich source of repository at the server using the WSN technology. An algorithm is proposed to detect 'power theft' in electrical distribution systems, based on the power monitoring module and the data collected in the server. The same has been successfully demonstrated through experimentation. Different wireless communication technologies have been used to communicate the data to the server from the power monitoring system.

1.4 Possible Communication Technologies for Power Monitoring

The basic communication architecture is simple and the actual network topologies can be very diverse and depend mostly on the field-level network. With respect to the communication requirements, several options are possible [8]-[11]. Wired communication with dedicated data networks connecting the field devices is one possibility. Dedicated wired data networks can be designed to fulfill the requirements, but the installation costs do not permit an intensive use [12]. A less expensive option is wireless networks. Technologies for wireless local area networks or personal area networks like IEEE 802.15.4 can, in principle, be used as a replacement for wired links [13, 14].

An alternate wireless technology is cellular networks as used in telecommunications, like global system for mobile communications (GSM) or General Packet Radio Service (GPRS), or Worldwide interoperability for Microwave Access (WiMAX). They have high coverage and low installation costs for the end devices if the infrastructure already exists [12]. The downside is the general dependency on the network provider if public telecommunication networks are used-regarding both costs for the communication channels and quality of service (QoS). A powerline communication system is another popular method for communication [14]-[18]. They use the existing power cabling and need only moderate additional network elements but require a more complex technology in order to overcome the rather poor communication channel characteristics. This type of communication needs higher technical effort and cannot be used in case of a disaster where the powerlines are disconnected. Recently, WSNs have been recognized as a promising technology that can enhance various aspects of today's electric power systems, including generation, delivery and utilization, making them a vital component of the next generation electric power systems, smart grids [15], [19]. Wireless sensor networks in conjugation with SCADA have been implemented in wind power plants. The wireless sensor network can provide abundant, real-time data for wind driven generators' reliable running, guaranteeing the steady running of wind power plant [20]. In Indian context of application of WSNs to power systems, new ideas and implementation plans are coming up where issues like power theft, automatic billing, monitoring of various parameters in the system, etc., are being dealt with [21]. The harsh environments of the power systems need properly designed wireless modules along with efficient sensing elements.

1.5 Proposed Power Monitoring System Architecture

The proposed power monitoring system architecture is shown in Fig 1.3. The entire system developed has a sensing module to sense the voltages and currents from which the power would be calculated. The power is computed using the sensed voltages and currents and the power value is sent to a base station through a wireless network. At the base station, the information related to the power is stored in the database. The information related to the power consumption is retrieved and can be processed further for different applications. The server to which the base station is connected has an appropriate graphical user interface (GUI) for the effective monitoring of power at various nodes. The power being measured is the average real power. The power sensing module computes

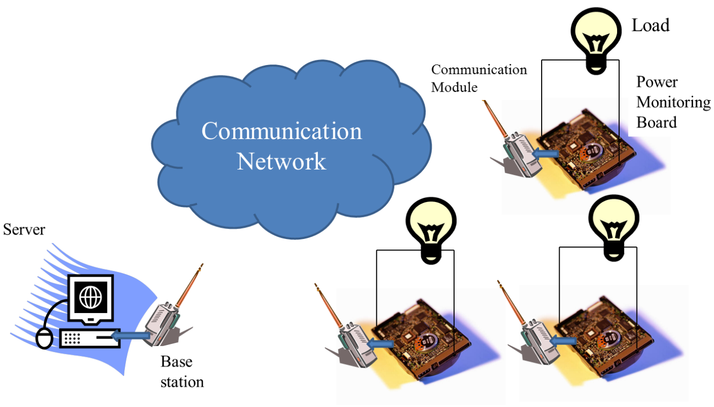

Figure 1.3: System architecture for power monitoring system

the average real power and communicates the real power information to the server which is a rich repository of information of real power which can be used for analysis of the distribution system. The first requirement of the power monitoring module is the sensing of the voltages and currents.

1.6 Existing Sensing Technologies and Processing

Existing sensing technologies for the voltage and current measurement are mostly the potential and current transformers. Potential transformers (PT) are used to measure high voltages. It is essentially a voltage step-down transformer that steps down the voltage to a measureable value. The stepped down voltage can be sampled to get the digitized voltage wave which can be processed to be used further.

The main instrument for current sensing used is the current transformer (CT), which is essentially a voltage step up transformer used to step down the value of the current to be measured [22]. There are new and advanced sensors for measuring lower currents like the Hall-effect sensors. But in case of the distribution systems, the currents will be in hundreds of amperes and the use of CTs is inevitable. The CTs and PTs when used to sense the voltages and currents for further processing of the sensed parameters, results in the most error free inputs to the processing unit or the processing circuit. The instrument transformers have very small errors when compared to the other sensing methods for voltages and currents.

The voltages and currents once sampled are used to compute the power corresponding to the voltages and currents. The other parameters related to the power system like harmonics, power factor, real and reactive powers, etc., can also be calculated. The measurements can also be used to infer the condition of the systems like, it can be known if the system is overloaded, unbalanced, etc. *The objective of this project is to mainly focus on the design of a power monitoring circuit which computes the real power and communicates the real power information to a server using a wireless network and to build novel applications based on the system.*

1.7 Organization of the Thesis

Chapter 2 discusses the basic architecture of a WSN and the network topology used in the present work to setup the network. Chapter 3 describes the basic block diagram and the circuit development for the power monitoring module. Chapter 4 discusses the experiments and the validation of the boards developed. Chapter 5 describes the implementation of the power theft detection algorithm as a proof of concept. It also discusses other applications and the further developments that can be done using the concept of wireless power monitoring.

1.8 Summary

In this chapter, we discussed the issues in Indian power systems, need for power monitoring and the communication technologies that can be used for power monitoring. As part of this work, a power monitoring system architecture based on WSN technology is proposed to overcome the hurdles faced in the distribution system. The wireless communication technology that is used for the system is described in the following chapter.

Chapter 2

An Overview of Wireless Sensor Networks (WSN)

In this chapter, the wireless sensor networks and its components are discussed. It also highlights the important network topologies, routing algorithms and the hardware used to setup the WSN in the present work.

2.1 Wireless Sensor Networks

A wireless sensor network (WSN) consists of spatially distributed autonomous sensor nodes to *monitor* physical or environmental conditions (such as temperature, sound, vibration, pressure, motion or pollutants) and pass their data through the network to a main location (base station). The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in many industrial and consumer application, such as industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control. Modern sensor networks are bi-directional and the sensor nodes talk among themselves. The bi-directional feature in the sensor networks allows the control actions to be communicated based on the sensed data transferred by a sensor node. This bi-directional feature in the WSNs has motivated to develop many industrial applications which are not only used for monitoring but also used for actuation or control. For example, the applications of WSNs in a wind power station or a wind farm.

In a wind farm, several parameters from the machine connected to the wind mill are communicated to the base station or the server which sends an actuation signal back to the sensor node. Parameters like wind-speed, wind-direction and speed of the generator are communicated to the server and based on this data the server sends an actuation signal back to the wind mill. The control action can be either manually done or can be automated. The wind-vanes of the wind mills are aligned according to the wind direction. The speed of the wind-vanes and the speed of the generator are the inputs to the gear system in the wind mills to regulate the speed of the generator to have the required terminal voltage for the power generated [20]. There are several other such applications of

WSNs that use bi-directional communication within the network.

2.2 Architecture of WSN

The basic architecture of a wireless sensor network is shown in the Fig 2.1. It mainly consists of a set of wireless sensor nodes (motes), a communication network and a base station which is also a sensor node but is connected to a server or a computer.

- The *sensor node* is the one which is deployed in the field or the location that is to be monitored. The sensor node is equipped with the appropriate sensors and the radio section for transmitting the data. To interface the sensor and the radio section a microcontroller is used. The main function of a sensor node is to sense the information, process the information and send it to the base via a network. Sensor nodes are densely deployed either very close or directly inside the phenomenon to be observed. Therefore, they usually work unattended in remote geographic areas.
- The *Base station* is the one that collects all the data from the sensor nodes via the network and then sends it a server or a computer for further processing of the data. In some cluster based networks (briefed later in this section) the base station can also be the cluster head. The base station can be programmed to listen for data or in other words, just accept the data sent by the sensor node (mote) or can be programmed to ask for the required data from a particular mote. The second approach is called query based communication and this is used in the present experimental work to establish the wireless network.
- The *communication network* is a medium by which the data is communicated wirelessly. The network is formed by the sensor nodes which act as routers. In some cases they act as routers equipped with their own sensors. There are several types of communication networks that can be formed which is briefly discussed in the following section.

2.3 Communication Networks topology

Different topologies exist in the formation of communication networks such as tree, star, ring (shown in Fig. 2.2) and mesh shown in Fig 2.3 [23]. The star, ring and tree topologies are similar in the way the sensor nodes communicate i.e., the sensor nodes communicate with only one other node to receive or transmit. The star topology is the one in which all the sensor nodes connected only with the base station. The ring topology is the one in which the data is transferred from one part of the network to the other only through a specified path. The path is like the ring as shown in Fig 2.2. If a link in the ring topology collapses, the ring topology fails and the communication may collapse [24]. The tree topology is a hierarchical topology in which a node of one level receives the data only from another node below its hierarchical level. The top most level at this hierarchy is the base station. The Mesh topology is a more efficient topology when compared to the rest of them. The mesh topology is discussed in the next section.

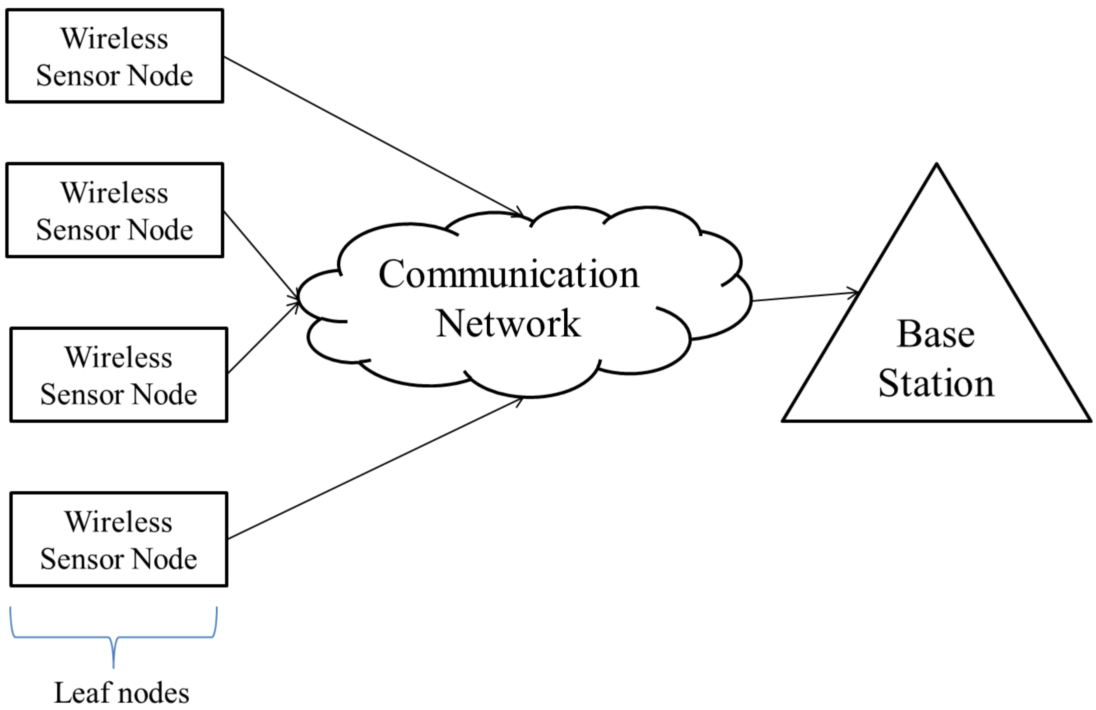

Figure 2.1: Basic architecture of a Wireless Sensor Network

2.4 Mesh Topology

Mesh networking (topology) is a type of networking where each node must not only capture and disseminate its own data, but also serve as a *relay* for other sensor nodes, that is, it must collaborate to propagate the data in the network. A mesh network can be designed using a *flooding* technique or a *routing* technique. When using a routing technique, the message propagates along a path, by *hopping* from node to node until the destination is reached [23], [24]. To ensure all its paths' availability, a routing network must allow for continuous connections and reconfiguration around broken or blocked paths, using *self-healing* algorithms. A mesh network whose nodes are all connected to each other is a fully connected network. The self-healing capability enables a routing based network to operate when one node breaks down or a connection goes bad. As a result, the network is typically quite reliable, as there is often more than one path between a source and a destination in the network. Although mostly used in wireless scenarios, this concept is also applicable to wired networks and software interaction.

Over the past decade the size, cost, and power requirements of radios has declined, enabling more radios to be included within each device acting as a mesh node. The additional radios within each node enable it to support multiple functions such as client access, backhaul service, and scanning (required for high speed handover in mobile applications). Additionally, the reduction in radio size, cost, and power has enabled the mesh nodes to become more modular-one node or device now can contain multiple radio cards or modules, allowing the nodes to be customized to handle a unique set

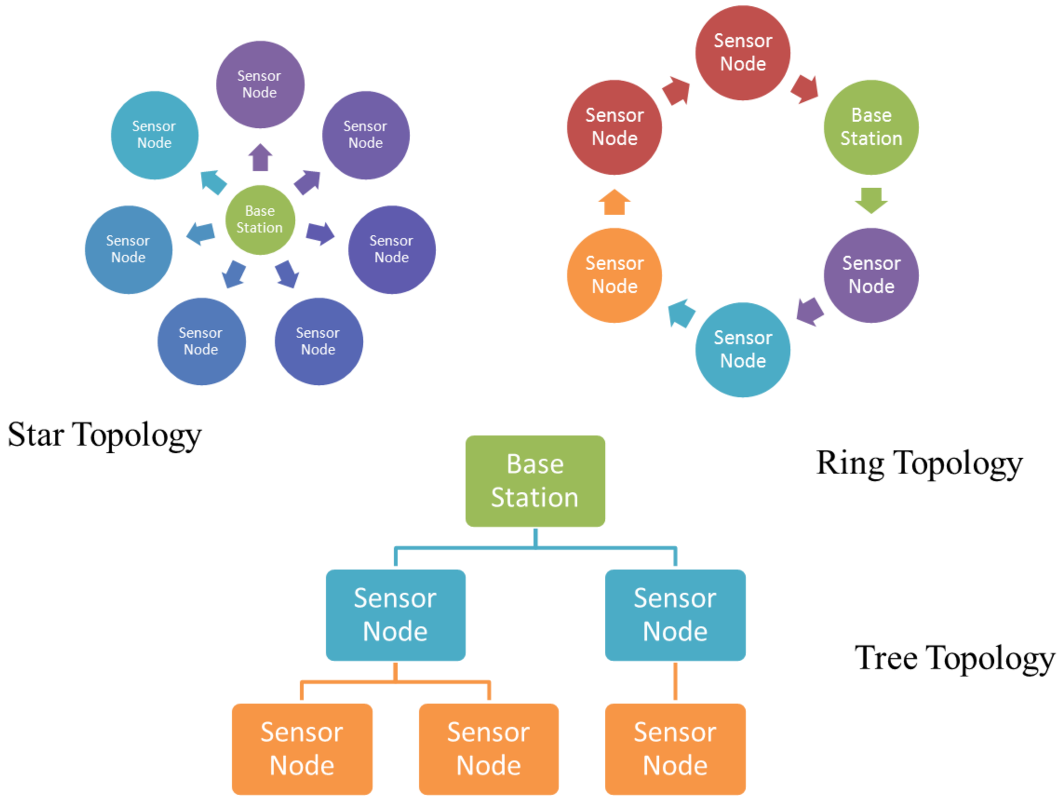

Figure 2.2: A diagram showing Star, Ring and Tree topologies

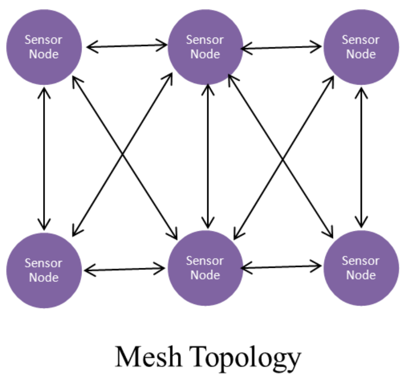

Figure 2.3: A typical Mesh topology of nodes in a network

of functions and frequency bands [25].

Any type of topology also has to be supported by a suitable type of routing the information through the network. The different types of routing are discussed in the next section.

2.5 Routing Algorithms

The process of communicating the data packets from one point to another in a network is called routing. A routing process involves a specific way of selection of path for the data transfer within the network. Some of the routing algorithms are: Dijkstra, Belman ford, link-state algorithms. There are different types of routing widely used. The type of routing can be based on the application being developed and the area of deployment. There are three main types of routing widely used:

1. Peer to peer routing
2. Single hop routing
3. Multi-hop routing

2.5.1 Peer-to peer routing

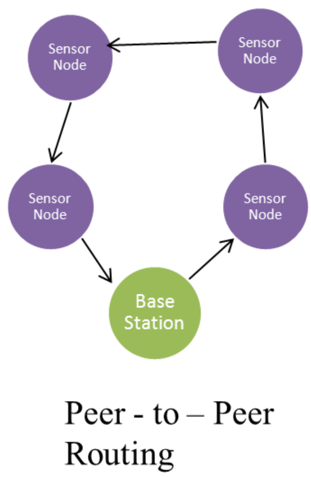

Figure 2.4: A representation of Peer-to-peer routing

Peer to peer routing (Fig 2.4) is the one in which a node sends or receives information only from one other node. This node pair is a fixed one in a network. This type of routing can be seen in tree topology and ring topology. The nodes can be anywhere in the hierarchy of the network. This type of routing is not used much lately as most of the networks are migrating towards mobile networks.

2.5.2 Single hop routing

Single hop routing is similar to peer-to-peer routing but one of the node in the pair is always the base. In this type of routing each node directly interacts with the base station. Single hop routing has a constraint of distance and the nodes cannot be distributed over a large deployment area. From Fig 2.5, it can be seen that the nodes that are not in range of the base station cannot communicate to the base. The single hop routing is the simplest routing algorithm.

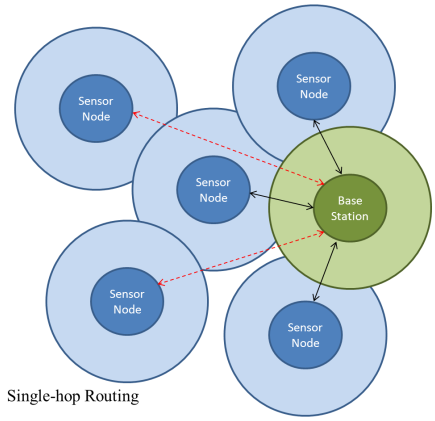

Figure 2.5: A representation of Single-hop routing

2.5.3 Multi-hop routing

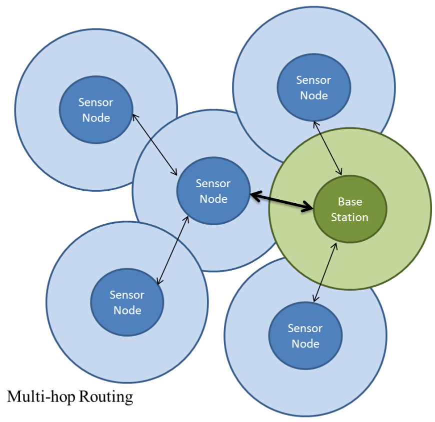

Figure 2.6: A representation of Multi-hop routing

Multi hop routing is the one in which the data from the sensor nodes reaches to the base in multiple hops. This indicates that the sensor node out of range of the base can also communicate to the base station through the other nodes as seen in Fig 2.6. The path of the data transfer need not be fixed and the data transfer can take different paths different time depending on the health of the network. This type of routing is called dynamic routing where the path of data transfers changes. This means that if a node fails, the network must be auto-reconfigurable so that each node can communicate with the data collector. Of course, appropriate routing protocols are necessary to discover routes between the source and the destination, or even to determine the presence or absence of a path to the destination node [24]. Dynamic multi-hop routing is the most efficient type of routing to transfer data for a largely deployed network.

2.6 The Mesh Network Used To Develop WSN Based Power Monitoring System

The network used to deploy the WSN in the present application is a multihop routing called *XMesh* [26]. XMesh is a full features multi-hop, ad-hoc, mesh networking protocol developed by Crossbow for wireless networks. XMesh is a software library, using TinyOS operating system that runs on embedded devices called motes. In this case the IRIS motes are programmed to communicate using the XMesh protocol. XMesh provides a true Mesh networking service that is both self-organizing and self-healing. XMesh can route data from nodes to the base station (upstream) or from base station to the all nodes or a specific node (downstream). It can also broadcast within a single area of coverage or arbitrarily between any two nodes in a cluster. Quality of Service (QoS) is provided by either a best effort (link level acknowledgement) and guaranteed delivery (end-end acknowledgement). Also, XMesh can be configured into various power modes including high power (HP), low power (LP) and extended low power (ELP) [26]. The *XMesh* networking protocol has various options including low-power listening, time synchronization, sleep modes, any-to-base and base-to-any routing. All Crossbow sensor and data acquisition boards that can make up a wireless sensor network are supported with *XMesh* enabled applications. The network uses the IRIS mote by cross bow to setup the network.

2.7 IRIS Mote Description

IRIS mote is an ultra-low power wireless module for use in wireless sensor networks, monitoring applications, and rapid application prototyping. IRIS mote leverages industry standards like IEEE 802.15.4 to interoperate seamlessly with other devices. By using industry standards, integrating humidity, temperature, and light sensors, and providing flexible interconnection with peripherals, IRIS mote enables a wide range of mesh network applications [27]. With TinyOS support out-of-the-box, IRIS mote leverages emerging wireless protocols and the open source software movement. IRIS mote is part of a line of modules enabling the easy compatibility of interfacing any sensor board to it. IRIS mote is shown in Fig 2.7 and Fig 2.8

Key features:

- 250 kbps, 2.4 GHz IEEE 802.15.4 ATmel Transceiver
- Interoperability with other IEEE 802.15.4 devices
- Atmel ATmega1281 with 8k RAM and 128k programming flash and 512k serial flash
- Integrated ADC, DAC, Supply Voltage Supervisor, and DMA Controller
- Integrated onboard antenna with 50m range indoors / 300m range outdoors
- Ultra low current consumption
- Fast wakeup from sleep (<6 μ s)
- Hardware link-layer encryption and authentication

- 51-pin expansion support to interface any sensor board
- TinyOS support: mesh networking and communication implementation.

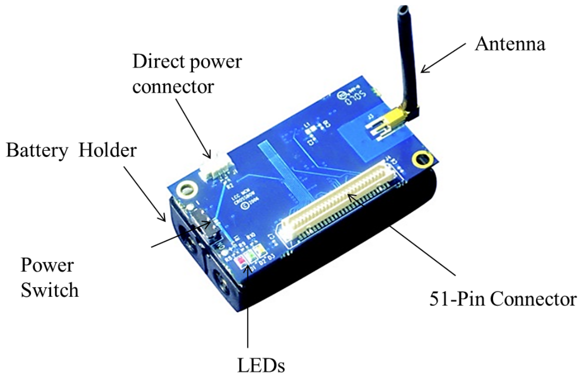

Figure 2.7: Photograph showing different parts of the IRIS mote (top side)

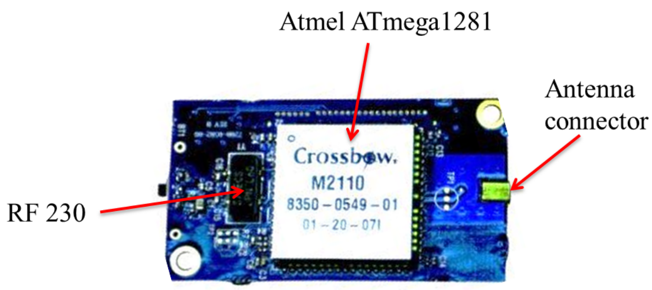

Figure 2.8: Photograph showing different parts of the IRIS mote (under side)

2.8 MDA 300

MDA300CA, shown in Fig 2.9 is designed as a general measurement platform for the IRIS motes [28]. Its primary applications are a) wireless low-power instrumentation, b) weather measurement systems, c) precision agriculture and irrigation control, d) habitat monitoring, e) soil analysis and f) remote process control.

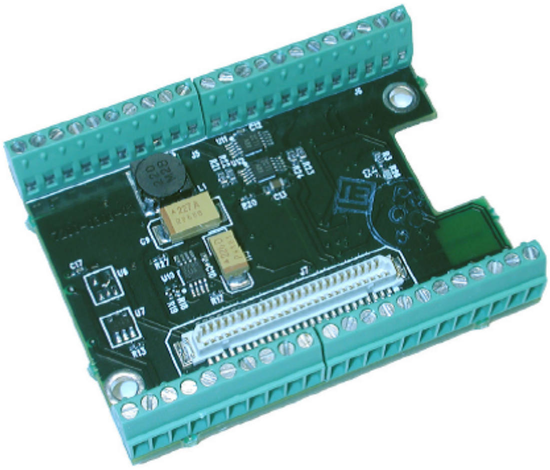

Figure 2.9: MDA300 Data acquisition and Sensor board

Analog sensors can be attached to different channels based on the expected precision and dynamic range. Digital sensors can be attached to the provided digital or counter channels. Mote samples analog, digital or counter channels and can actuate via digital outputs or relays.

2.9 Software Required For IRIS Mote

2.9.1 TinyOS and nesC programming language

The TinyOS system, libraries, and applications are written in nesC, a new language for programming structured component-based applications. The nesC language is primarily intended for embedded systems such as sensor networks. nesC has a C-like syntax, but supports the TinyOS concurrency model, as well as mechanisms for structuring, naming, and linking together software components into robust network embedded systems. The principal goal is to allow application designers to build components that can be easily composed into complete, concurrent systems and yet perform extensive checking at compile time [29].

2.9.2 Moteview

MoteView is designed to be an interface ("client tie") between a user and a deployed network of wireless sensors. *MoteView* provides the tools to simplify deployment and monitoring. It also makes it easy to connect to a database, to analyze, and to graph sensor readings [30].

Figure 2.10 depicts a three-part framework for deploying a sensor network system. The first part is the Mote layer or sensor mesh network. The Motes are programmed with *XMesh*/TinyOS firmware "application") to do a specific task: For example, environment monitoring, asset tracking, intrusion detection, etc. The second layer or Server tier provides data logging and database services.

At this layer, sensor readings arrive at the base station (IRIS connected to MIB520) and are stored on a server. The third part is the client tier in which software tools provide visualization, monitoring, and analysis tools to display and interpret sensor data. The third part of the software can be configured manually to behave as an appropriate GUI for the application developed.

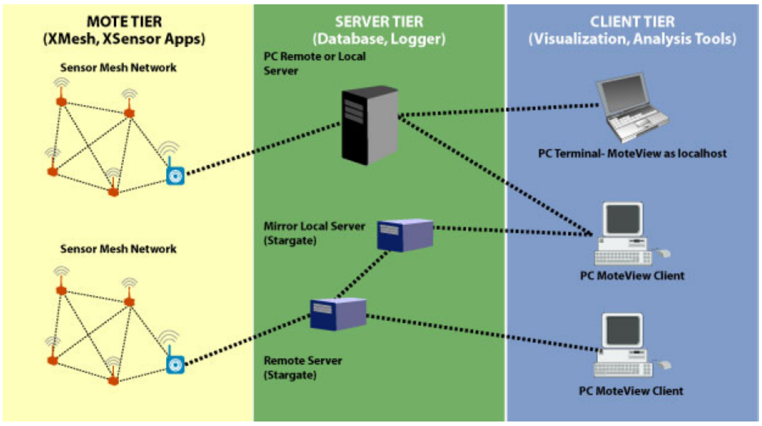

Figure 2.10: Software framework for WSN in Moteview [30]

2.10 Summary

A basic idea of WSN is established and the types of topologies and routing are understood. The hardware used for developing the WSN is explained. The software used to program these motes and the basic structure of the GUI Moteview is also explained in this chapter. In the next chapter we would discuss the proposed power monitoring system based on WSN.

Chapter 3

System Architecture for Power Monitoring Using WSN Technology

3.1 Introduction

In this chapter, the architecture for the proposed power monitoring system based on the WSN technology is discussed. The power monitoring system using WSN has a modular architecture as shown in Fig 3.1. The architecture shown in the figure is for a single node, which computes power and sends this information to the base station.

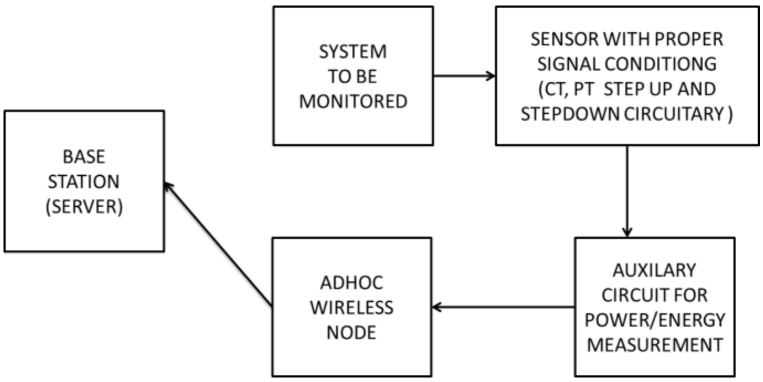

Figure 3.1: System architecture initially planned for the power monitoring system

The main blocks in the power monitoring module are as follows:

1. Sensing the voltages and currents
2. Signal conditioning
3. Power calculation

4. Interfacing to the communication module
5. Communication to the server

3.2 Sensing The Voltages and Currents

To calculate any parameter in an electrical power system, the data on voltages, currents and the phase difference between them are primarily required. These data can be obtained by measuring the voltage and current waveforms simultaneously and digitizing them with appropriate sampling rate for further processing. This digitizing process was attempted using the ADC channels on the MDA 300 sensor board, however it was unsuccessful as the access to the ADCs is not in parallel but the ADCs were being accessed serially and so the phase information was lost. To further analyse on MDA 300, experiments were conducted to sample 50 Hz sinusoidal signal generated from the signal generator. The least sampling time that can be set is 1 ms, which is not accurate enough for a 50 Hz signal. The error involved would be significant and would increase when there are two voltages to be measured simultaneously. The parallel sampling was therefore not feasible with MDA 300 sensor board [28].

It was then decided to use an auxiliary circuit to accurately sample the voltage and current waveforms and to compute the real power. The real power information could then be sent to the base station and then to the server, which has a configured GUI to display the required information. A single phase energy metering IC ADE 7757 was used to compute the real power from the sensed voltages and currents after appropriate signal conditioning. The signal conditioning is necessary to modify the signal to meet the input requirements of the ADE 7757.

3.3 Signal Conditioning

The sensed voltages and currents need to undergo suitable signal conditioning to be used to calculate the power. The voltages and currents were stepped down to be fed to the ADE 7757 to compute the real power consumed by the load. The schematic of the step down circuitry used to give appropriate inputs to ADE 7757 is shown in Fig 3.2. A resistance potential divider is designed, where the values of the resistances were appropriately chosen using the Equation 3.1. The resistance potential divider suits this case as there is no change in supply voltage waveform. Other methods of potential dividers using capacitances may lead to the waveform distortions.

$$V_1 = \frac{R_1}{R_1 + R_2} V_{PN} \tag{3.1}$$

Where,
V_1 is the input voltage to the IC ADE 7757.
V_{PN} is the phase to neutral voltage of the electric power source.
R_1 & R_2 are the resistors dividing the voltage.

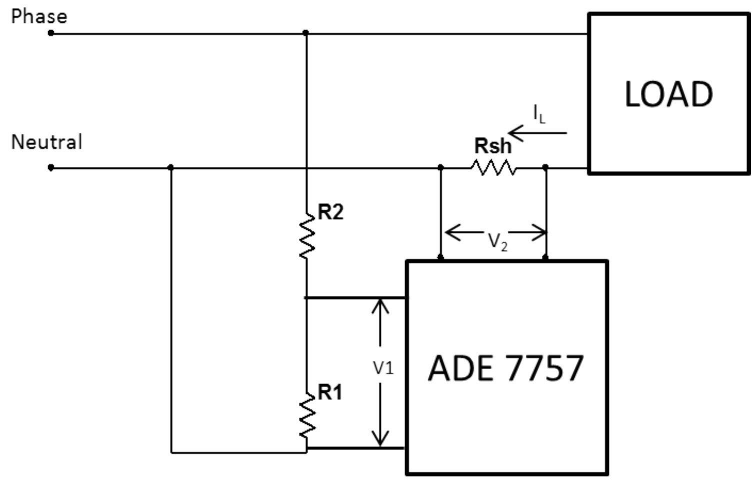

Figure 3.2: Schematic showing the step down schemes for voltage and the current inputs to the energy metering IC ADE 7757

The current measurement was not straightforward as it was not easy to design a current measuring scheme for all currents using a single technique. To measure the current with the least loading a shunt resistor was used. The resistance of the shunt needs to be very low as it should not cause loading. The current measurement in this case is done in an indirect way. As the resistance is constant, the current is the scaled version of the voltage across the shunt, which can be computed using Equation 3.2

$$I_L = \frac{V_2}{R_{sh}} \tag{3.2}$$

Where,

I_L is the load current

V_2 is the voltage across the shunt resistor. This voltage is also the input to the current channel of ADE 7757

R_{sh} is the shunt resistance to measure the current in terms of the voltage.

The values of the resistances are calculated using the Equations 3.1 and 3.2 are

$$R_1 = 500\Omega$$
$$R_2 = 1.8M\Omega$$
$$R_{sh} = 350\mu\Omega$$

These values were calculated based on inputs from the datasheet of ADE 7757 [31].

3.4 Power Calculation

The heart of the power monitoring system is the energy metering IC which computes the real power consumed by the load. The energy metering IC by Analog Devices is a single phase energy metering IC, ADE 7757. The functional block diagram of ADE 7757 is shown in Fig 3.3.

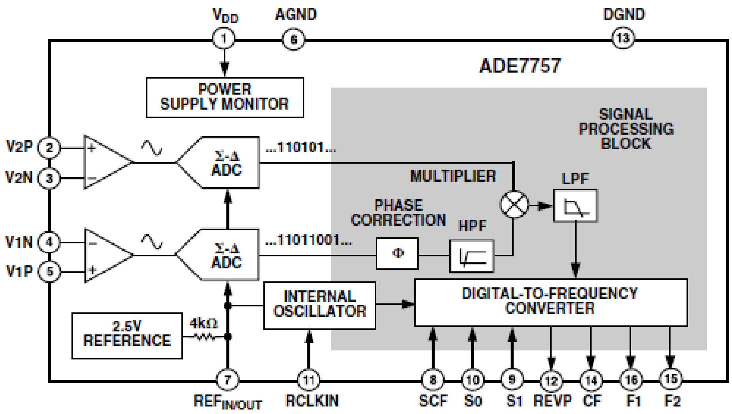

Figure 3.3: Functional Block Diagram of ADE 7757 [31]

The functioning of ADE 7757 can be easily understood by the block diagram. The chief blocks in ADE 7757 are:

1. The ADCs
2. Phase correction and high pass filter (HPF)
3. Multiplier
4. Low pass filter (LPF)
5. Digital to frequency converter

The ADCs take the input in analog form and digitizes it to be fed to the processing section of the IC. The Processing section begins with the conditioning of the voltage and current signals from the ADC to the multiplier. The phase corrections block in the current channel corrects the phase lead produced by the HPF. The HPF is used to remove any dc offset value in the current waveform. The offset may be present as the current is not directly fed but is converted to a corresponding voltage. The multiplier multiplies the two signals to generate a corresponding voltage that is proportional to the power. Equations 3.3, 3.4 and 3.5 show different representations of power. The ADE 7757 computes the real power as it is of concern in the distribution system. The term "power" from this point onwards refers to the real power. The power thus computed will be of double the supply frequency and will oscillate about a dc value corresponding to the power. To extract this DC value a LPF is used. The DC value corresponding to the power is then converted to a pulse waveform by the digital to frequency converter [31]. The IC is developed as an energy metering IC and therefore the pulses can be used to run a recording mechanism. In the present application, the IC is being used to compute the average real power consumed by the loads. Therefore, the pulses need to be processed further which is discussed in the following section.

$$ApparentPowerP = V_{rms}I_{rms} \tag{3.3}$$

$$RealPowerP_r = V_{rms}I_{rms}\cos(\Phi) \tag{3.4}$$

$$ReactivePowerP_i = V_{rms}I_{rms}\sin(\Phi) \tag{3.5}$$

The IC is developed as an energy metering IC and therefore the pulses can be used to run a recording mechanism. In the present application, the IC is being used to compute the average real power consumed by the loads. Therefore, the pulses need to be processed further which is discussed in the following section.

3.5 Interfacing The Communication Module

The power computed needs to be sent to the server or a PC. The communication modules being used are the IRIS motes discussed in the Chapter 2. The power information is converted to a suitable form to be sent to the server. The interface to the communication module and the ADE 7757 needs an additional circuitry to convert the frequency signal (the output of the energy metering IC). The additional circuitry functions to count the number of pulses in a given time, in other words it is the frequency measurement that is needed to measure the power consumed by the load.

3.6 Communication with The Server

Communicating the power measured to the server and displaying the information in a meaningful way is an important part of the power monitoring system using WSN. The server is usually a pc connected to the base station. An appropriate graphical user interface (GUI) needs to be equipped with database management system to store the data. The base station receives the data from different nodes monitoring different loads and sends the information to the server. The base station is connected to the server using the MIB 520 through a USB port.

3.7 Detailed Block diagram and functioning of the Power Monitoring System

The WSN based power monitoring system developed has several blocks apart from the main power computing IC ADE 7757 and the communication modules. The detailed block diagram of the system designed is shown in Figure 3.4. The block diagram consists of all the additional blocks required to interface the power monitoring module and the communication.

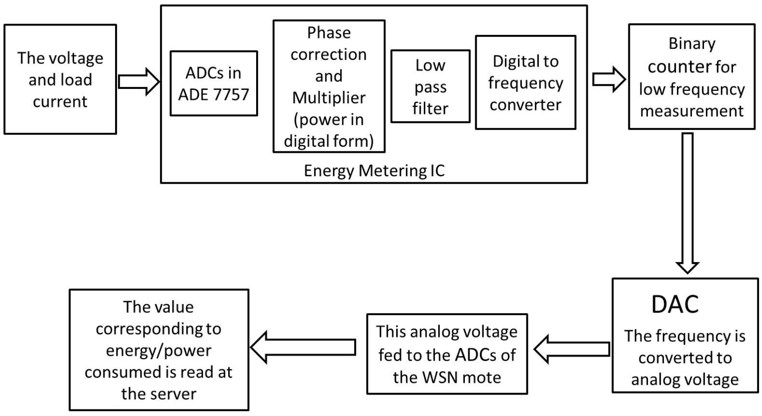

Figure 3.4: Detailed block diagram of the WSN based power monitoring system

The voltage and the load current inputs are given to the energy metering IC (ADE 7757) after appropriate stepping down and conditioning as was discussed in Section 3.3. The output of ADE 7757 is in terms of pulses and the frequency of the pulses is dependent on the load being monitored. The MDA 300 sensor boards have a counter channel which can be used for high frequency measurement [28]. Experiments conducted on MDA 300 showed that frequency greater than 3 kHz can be measured accurately. But the frequency generated by the ADE 7757 is a very low frequency of the order of 83 to 250 mHz (for the loads tested till 360 watts: The related experimentation is explained in the next chapter). This is a very low range of frequency when compared to the range that MDA 300 can measure. However the counter channel gives the frequency measurement in terms of the number of pulses the channel counts in a given time. For direct frequency measurement it is necessary to access the counter channel every 1 second, else the reading will only be a count and not the frequency. Thus, the counter on MDA 300 could not be used to interface ADE 7757 to the IRIS motes for communication.

An auxiliary circuit to measure the frequency of the pulses which is a measure of the average real power consumed by the loads is designed. The auxiliary circuitry as shown in Fig 3.6, consists of a 8-bit binary counter and a digital to analog conversion unit.

The counter is clocked by the pulses generated by ADE 7757 and hence the counter counts the number of pulses in the output of the metering IC. To interface the counter output to the MDA 300 was also not feasible as there are only 6 digital channels and the counter had 8 bits. If the bits of the counter output were to be sent serially, a dedicated microcontroller needs to be used which is not economical.

Therefore a digital to analog converter (DAC) was designed using the tested and proved R-2R ladder network. To verify if the ADC channels of the MDA 300 sensor board responds well to the direct current (DC) values, experiments were conducted using the regulated power supply. The DC voltage given as inputs to the ADC channel of MDA 300 was sent to the base station and the server read the voltages accurately. Fig 3.5 shows the experiment with DC values being performed.

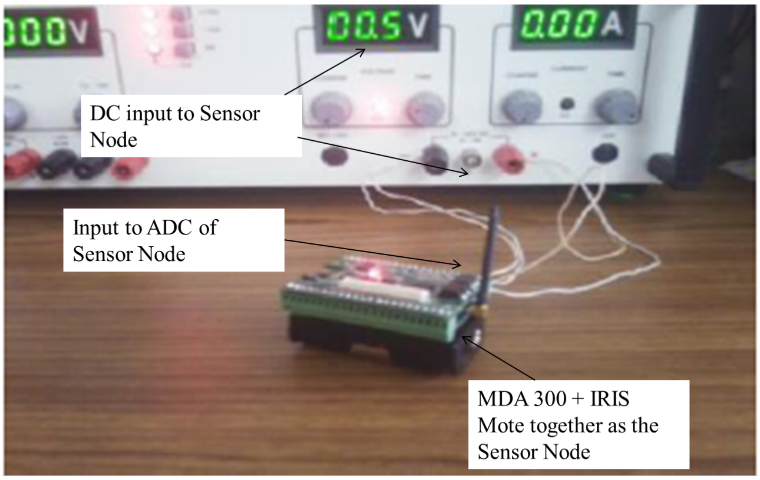

Figure 3.5: Experiment conducted with the DC voltage transmitted to the server

The DAC is the best possible solution to measure the power which is output as the frequency from the ADE 7757. The DAC output depends on the counter's output which in turn depends on the output of ADE 7757.

The output frequency of the ADE 7757 can be given by the Equation 3.6, which is transfer function mentioned in the datasheet of ADE 7757.

$$F_0 = \frac{515.84 * V_1 * V_2 * F_1}{V_{ref}^2} Hz \tag{3.6}$$

Where,

F_0 is the frequency of the output pulse in Hz

V_1 is the voltage input to ADE7757 from Eqn 3.1 in Volts

V_2 is the voltage proportional to load current from Eqn 3.2 in Volts

V_{ref} is the reference voltage for internal blocks (3.3 volts) in Volts

F_1 is the frequency generated in the IC and is given as 0.86 Hz for the configuration designed [31].

Substituting the values of the resistances in the Equations 3.1, 3.2 and 3.6, the frequency and the power relation can be derived as shown in Equation 3.7.

$$F_0 = 1.59 * 10^{-3} V_{in} * I_L \quad Hz \tag{3.7}$$

Based on the above descriptions and requirements the circuit with ADE 7757 was developed as the power monitoring module. This module facilitates the easy measurement of power for a single phase system. The circuit designed to develop the power measuring module is shown in Fig 3.6. The reference design of the rest of the circuit components is taken from the datasheet.

The design of the circuit will not change drastically for different loads to be monitored. However, the part measuring the load current may have to be changed with a suitable conductor diameter to allow the load current to flow. Another solution to this issue is to use a CT of a suitable rating such that the secondary of the CT is connected to the Rsh (350 μ Ω resistor). The calculation of the output power requires the CT ratio to be taken into account if CT is being used.

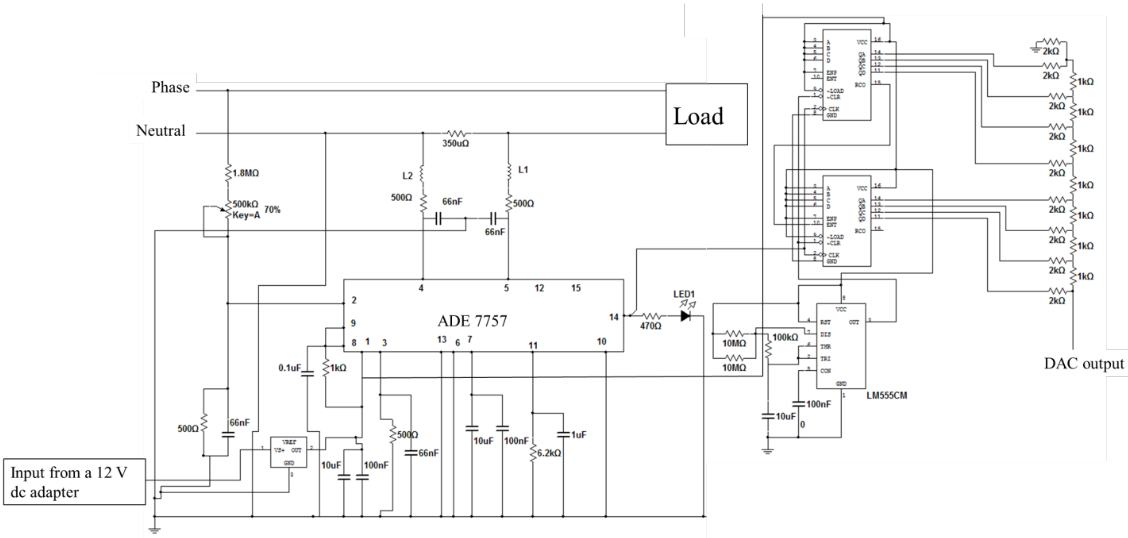

Figure 3.6: Circuit diagram of the power monitoring module

This chapter successfully explains the functioning of the power computation block of the WSN based power monitoring module developed.

3.8 Summary

In this chapter, the proposed architecture for the power monitoring system based on WSN is discussed. We will discuss the experimentation performed on this module in the following chapter.

Chapter 4

Deployment and Experimentation of Proposed Power Monitoring System based on WSN

In this chapter, the deployment and the experiments performed on the proposed power monitoring system based on WSN is discussed. Calibration of the boards is also described. The development of the system using a GSM module for communication of power information is also discussed.

4.1 Deployment of Power Monitoring System based on WSN

A wireless sensor network consists of several sensor motes along with a base station connected to the server. A multi-hop mesh WSN as shown in Fig 4.1, is setup using IRIS motes (Fig. 2.7) and a data acquisition board MDA300 (Fig 2.9).

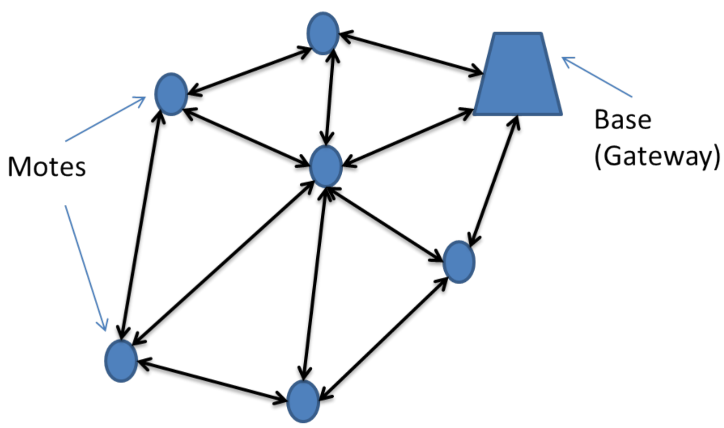

Figure 4.1: Multi-hop mesh network

The multi-hop network was set-up by programming the motes in TinyOS using nesC [29]. Multi-hop mesh network is capable of dynamic routing which enables the motes to communicate to the base station directly if it were in range (about 100m line of sight) or through other motes in range.

The initial experiments with the signal generator for testing the performance with the ac signals helped to understand the performance of the data acquisition board (sensor board MDA 300). The performance of the MDA 300 was also studied for different dc voltages and hence the output of the power monitoring module i.e., the DAC output was given to one of the ADC channel of the MDA 300. The MDA 300 samples the ADC channel and sends the information to the main communication module, the IRIS mote. The IRIS constructs the data packets to be transmitted to the base station which is connected to the server.

The wireless sensor network with the IRIS motes connected to the power calculating module through the MDA 300 sensor board. A single power monitoring module with the sensor board connected to the IRIS mote is shown in Fig 4.2. The pulses generated by the metering IC are then used to drive a counter which is connected to a DAC which has an output equation of

$$V_{out} = V_R * \sum_{i=1}^{8} C_i * \frac{1}{2^i} volts \tag{4.1}$$

Where,

V_{out} is the output of the DAC

V_R is the reference voltage (1.5 V in this case)

C_i is the value of the i^{th} bit in the counter

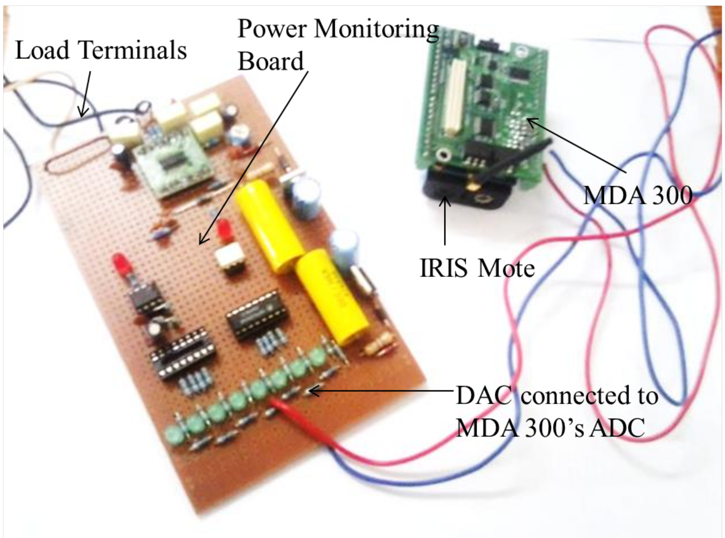

Figure 4.2: A single power monitoring module connected to the IRIS through MDA 300 data acquisition board.

The DAC output is then mapped back to the power value based on the counter value, the reset time of 59 secs and the derived relation for frequency of pulses to the power. The counter needs to be reset at regular intervals else the counter may overflow. A 555 timer was used to generate a reset signal every 59 seconds. The theoretical calculation can be done directly from the voltage value of the output of the DAC. However, for the implementation of the WSN based power monitoring system, an appropriate GUI is needed. The GUI used in the present work, is the Moteview configured to act as a power monitoring GUI as seen in Fig 4.7. The configuration of Moteview software needs an equation to map the voltages transmitted by the nodes to the corresponding power values. The equation can be obtained by a one-time calibration of the power monitoring modules. The calibration of the boards is explained in the next section.

The power monitoring system using WSN technology shown in Fig 4.2 was tested using different loads. The loads that were tested were of known power rating and so the module could be tested to check if the output matched the actual load connected. The module was tested with 60, 100 and 200 watts incandescent lamps and a 14 watt compact fluorescent lamp. For example, a 60 watt bulb connected as a load to be monitored gave pulses approximately every 12 secs, resulting in 4 counts. The DAC output was found to be 189.8 mV also can be verified from Equation 4.1. Theoretically, the time for each pulse is 10.58 sec using equation 3.7. The difference between the theory and the practice was very minimal.

A three node network was setup to monitor different loads of 60 watts, 100 watts and 200 watts by using the system developed. The data was collected and sent to the base successfully at periodic intervals using the WSN network setup using IRIS motes.

4.2 Need for Calibration

The development of the boards involved a lot of electronic components whose characteristics vary due to factors in manufacturing units. The small variation in their characteristics affects the output of the system. If this has to be considered, calibration of the boards is needed.

4.3 Calibration of the Boards

The calibration is done experimentally and the value is determined by connecting known loads and checking the DAC output. The maximum DAC output should not exceed 2.5 volts which is the maximum input for the ADC channel of the sensor board [28]. The DAC is designed in such a way that this constraint is taken into account.

The steps involved in the experimental calibration are described below:

- The board is connected to a known load and the reading of the DAC is noted. This is repeated for several different loads to get an idea of how the output of the DAC varies with the load. Table 4.1 shows the tabulated readings.

- The data obtained is tabulated and an appropriate curve is fit to match the data. The curve is the calibration curve for the given board as seen in Fig 4.4 Matlab is used to fit the curves.

Care should be taken while loading the board to see that for the given load the counter counting the number of pulses should not overflow. Overflow of the counter will cause serious errors in the system developed.

If it is desired to monitor very heavy loads and if the counter overflows, the number of bits of the counter needs to be increased. As the counter is extended, correspondingly the DAC section also needs to be extended to meet the requirement.

However if a CT is being used then the ratio of the CT also should be taken into account while calibration. As the current sensed by the board, i.e., the voltage across the shunt resistor is only due to the current in the secondary of the CT which is not the exact load current, the CT ratio is an important part while calculating the power theoretically.

It also needs to be taken care that, for a given board the calibration with the CT and without the CT has to be done separately as the load current will not be the sensed current in case of use of CT for current measurement.

The experimental calibration is an important part of the power monitoring using WSN as the output from the board is only in terms of voltages and the GUI is the one which actually extracts the information of the real power from the voltages. This information can be obtained by the GUI only if it is configured with the appropriate voltages.

A photograph of the system being calibrated is shown in Fig4.3

From the Fig 4.3, it can be clearly observed that the reading of the output of the DAC is being measured by the digital multimeter. The voltages are measured for different loads being supplied and monitored by the power monitoring module.

The voltages are tabulated for every board by varying the loads being monitored. The set of voltages are then tabulated and by appropriate curve fitting, the calibration equation is obtained for each board.

4.3.1 Calibration curves for each board developed:

The calibration for the developed boards was done and the corresponding calibration curves along with the tabulated voltages are discussed in this section.

Calibration of board 1

(used as the source board later)

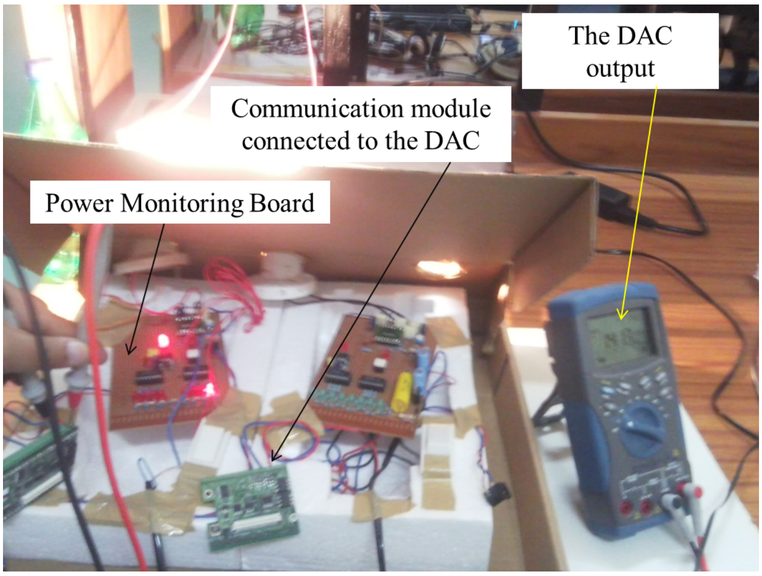

Figure 4.3: The setup for the calibration of the power monitoring module

The voltages are tabulated for the first board developed and the corresponding calibration equation is given below.

Table 4.1: DAC output voltages corresponding to the load power for board 1

Load(Watts)	DAC output(volts)
0	0.1272
60	0.1769
100	0.2144
160	0.2506
200	0.2632
260	0.3000
300	0.3343
360	0.3712

Calibration equation is given by equ 4.2

$$P = -17000v^3 + 14000v^2 - 1900v + 59watts \tag{4.2}$$

Calibration of board 2

The voltages are tabulated for the first board developed and the corresponding calibration equation is given below.

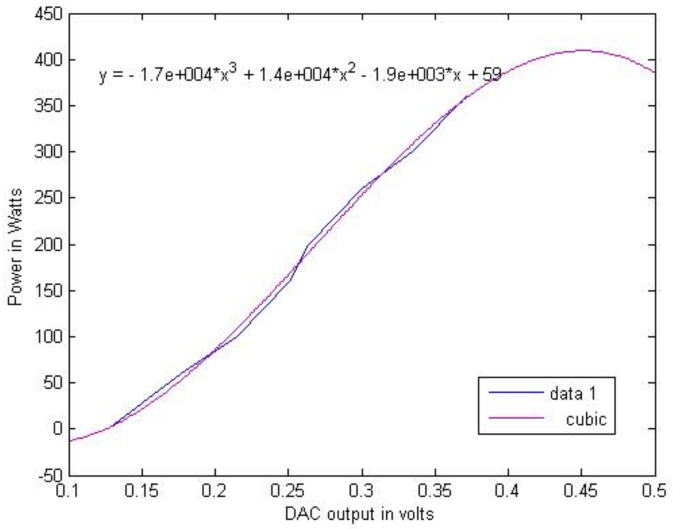

Figure 4.4: Calibration curve with equation for the first board designed

Table 4.2: DAC output voltages corresponding to the load power for board 2

Load(Watts)	DAC output(volts)
0	0.1323
60	0.1694
100	0.1938
200	0.2419

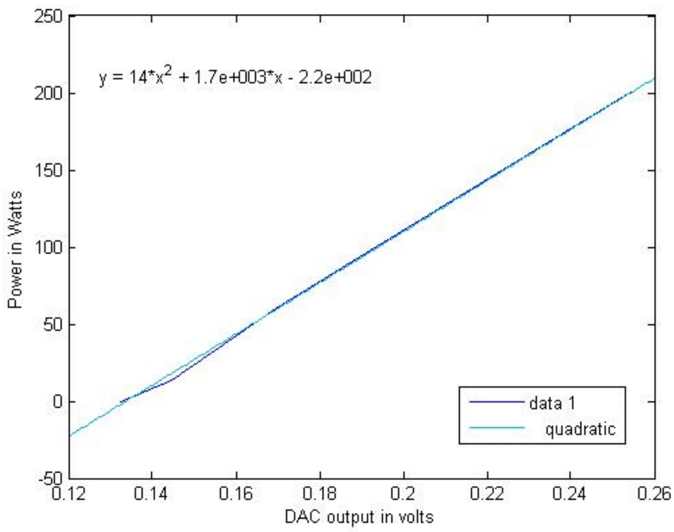

Figure 4.5: Calibration curve with equation for the second board designed

Calibration equation is given by equ4.3.

$$P = 14v^2 + 1700v - 220watts \tag{4.3}$$

Calibration of board 3

The voltages are tabulated for the first board developed and the corresponding calibration equation is given below.

Table 4.3: DAC output voltages corresponding to the load power for board 3

Load(Watts)	DAC output(volts)
0	0.1293
60	0.1789
100	0.2165
200	0.2768

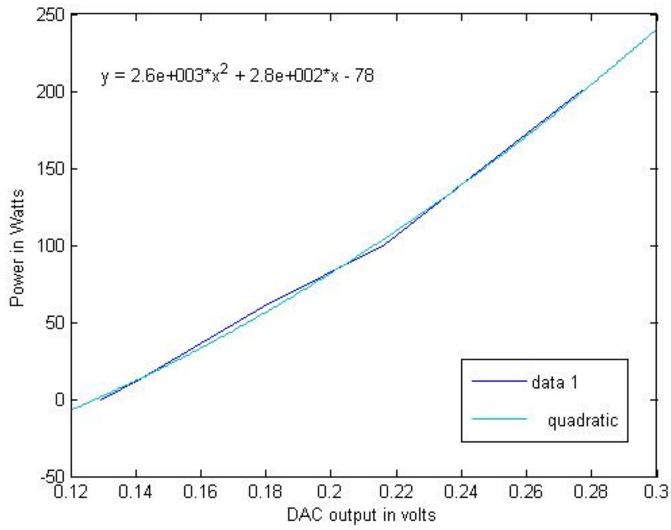

Figure 4.6: Calibration curve with equation for the third board designed

Calibration equation is given by equ4.4.

$$P = 2600v^2 + 280v - 78watts \tag{4.4}$$

Therefore, using the above calibration equations to configure the Moteview software as shown in

Fig4.7 , the complete WSN based power monitoring system can be realized.

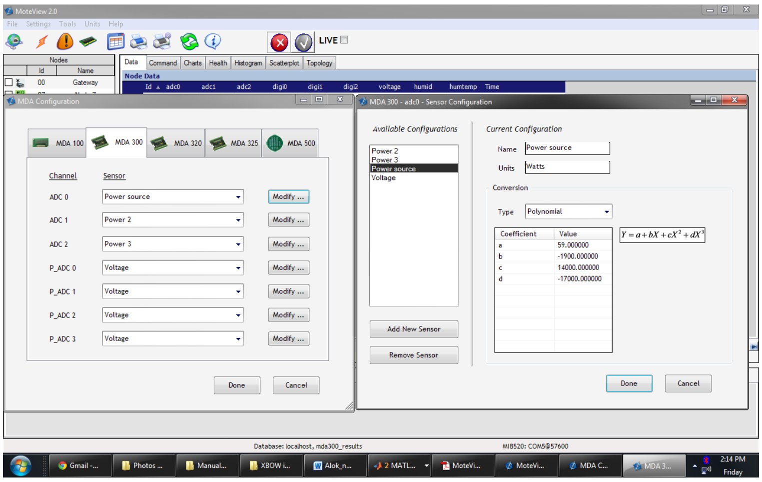

Figure 4.7: A screenshot showing how to configure Moteview for any sensor by providing its calibration equation

As seen in the figure any ADC channel of the sensor board can be configured to read the voltage and display the processed information from the sensed voltage at the ADC channel. In the present work different ADC channels are used for different power monitoring modules as the calibration equations are different.

The reason for the calibration equations to be different is that there have been design developments from the first board designed to the third board. The third board designed is the final version of design of the power monitoring module.

In the Fig 4.7 it can be clearly seen that the ADC channel 0 is being configured to monitor the first board referred to as the source board. The calibration equation coefficients are entered in the proper fields in Moteview to configure the software to act as a power monitoring GUI.

4.4 Wireless Power Monitoring Using GSM Technology

The same power monitoring modules were used to monitor the power consumed by different loads using GSM technology. The GSM communication module was implemented using 8051 microcontroller with the GSM module. The DAC output is connected to the ADC of the 8051 microcontroller. The 8051 was programmed to sample the ADC channels to measure the DAC's output voltage and process appropriately to compute the power using the calibration equation derived for the respective board connected.

The processed real power information was sent to a GSM SIM card whose number is predefined in the code in the microcontroller via the GSM module connected to the 8051 microcontroller. A

GSM module is interfaced to the microcontroller for communicating the power calculated. Fig 4.8 shows the power monitoring module interfaced to the GSM module through the 8051 microcontroller.

The power monitoring using the GSM technology for electrical power distribution system monitoring as the WSN with the sensor nodes has a constraint of distance whereas this constraint is eliminated in case of the GSM technology. The power distribution system monitoring can be enhanced further using the GSM technology to measure various other parameters like currents, voltages, etc. In the present work, the GSM technology was also successfully used to implement wireless power monitoring.

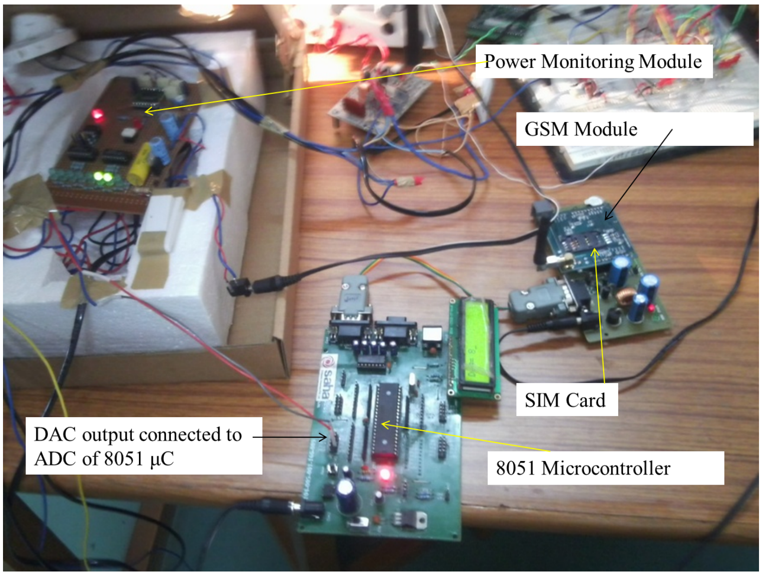

Figure 4.8: The implementation of power monitoring with the GSM module.

4.5 Summary

In this chapter experiments conducted to develop a WSN based power monitoring system was discussed. The boards need to be calibrated so that the error is minimized. The system developed with GSM can be improved to be used for distribution system monitoring as it has longer range. In the next chapter, we discuss a novel application based on the proposed power monitoring system.

Chapter 5

Power Theft Detection and Other Application of WSN Based Power Monitoring

This chapter discusses a novel application of the WSN based power monitoring system: “Detection of power theft”. It describes the simulation and implementation of the power theft detection algorithm as a proof of concept. It also discusses the other applications and the further work that can be developed using the module.

5.1 Power Theft Detection Using The WSN Based Power Monitoring System Developed

One important application of the WSN based power monitoring is to detect the theft of electric power. To thoroughly understand the situation a simple simulation was carried out using Matlab Simulink to use the power monitoring in conjunction with the communication module to study the behavior of the system as shown in Fig 5.1.

The simulation was used to study the entire system ie., sensing of voltages & currents, calculation of active powers and sending these values to the base station through a channel. The Simulink model has balanced 3-Φ voltage source with root mean squared (RMS) value of 230V. Two balanced 3-phase loads are considered with a lossy distribution line was modeled with resistance of 8Ω to get a maximum voltage drop of 6% across the line. The load powers were calculated with a loss-less line and the power mis-match between the source power and the load power was found to be 0W as seen in Fig 5.2. The same simulation was repeated with a lossy line and the power mismatch was equal to the loss in the line as seen in Fig 5.3. All the loads were modeled to be 150Ω per phase. The currents and voltages were sensed so that active power could be calculated. The values of voltages and power were transferred through an Additive White Gaussian Noise (AWGN) channel. The information could be sent successfully through the channel.

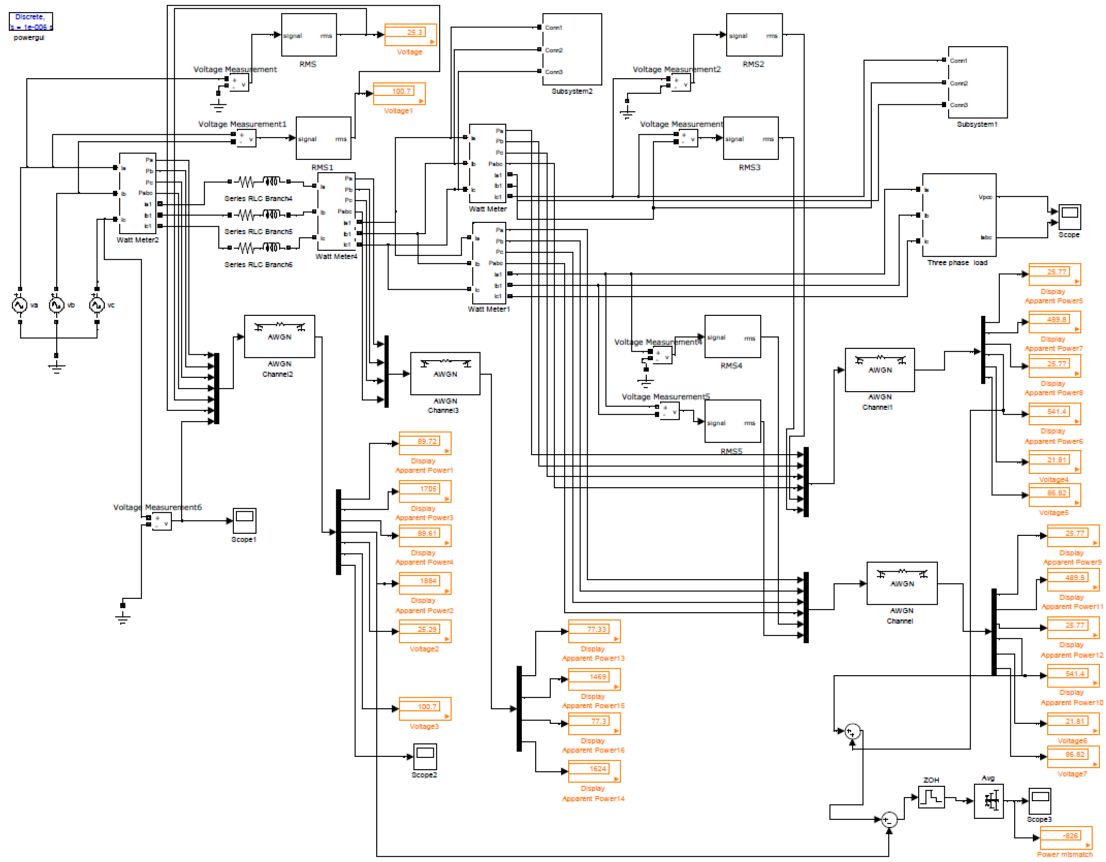

Figure 5.1: A screenshot showing the model file for the power theft detection

The above simulations were carried out with all the loads being monitored. To simulate a case of power theft, an un-monitored load was introduced and the power deficit was calculated which was equal to the sum of line loss and the stolen power as seen Fig 5.4. The simulation results are discussed below.

The model in the simulation was implemented in real time using the power monitoring system. The WSN based power monitoring system was implemented with three power monitoring modules and three nodes. Essentially, the system to be implemented consists of three nodes and a base station connected to the server with the GUI configured to act as a power monitoring GUI. The connection of the nodes in the system is shown in the block diagram (Figure 5.5). The figure shows the connection of the system for the implementation of power theft. This experiment can be extended to the real world problem with the source analogous to the end distribution transformer and the loads as consumers. The Load 3 behaves as the consumer stealing power from the end distribution transformer.

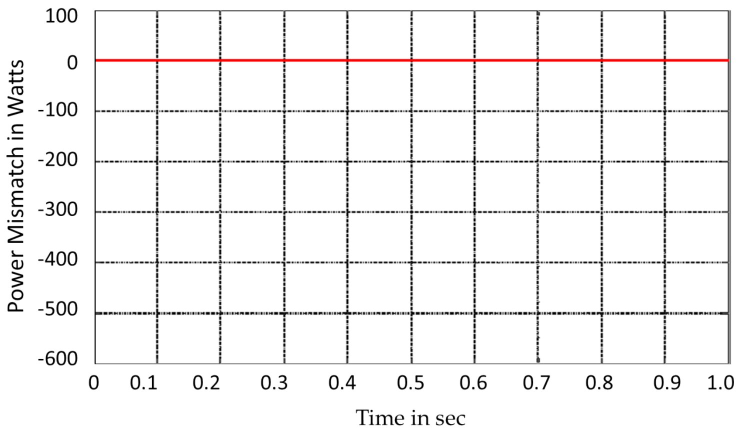

Figure 5.2: Power mismatch in case of a lossless line without power theft

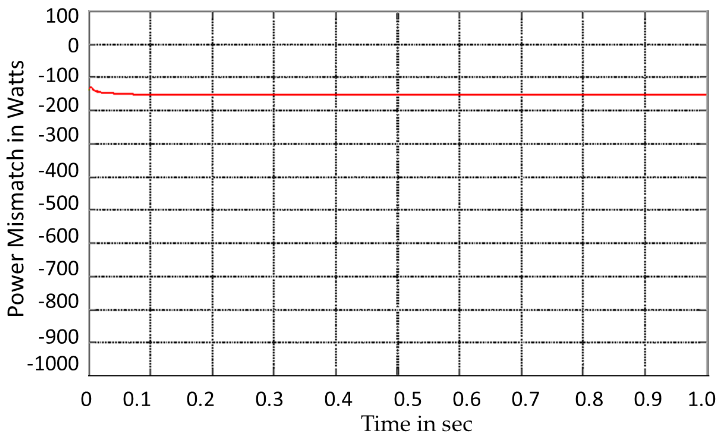

Figure 5.3: Power mismatch in case of lossy line without power theft

The source is supplying three loads of which two loads are monitored by two power monitoring modules. The third load is not monitored and behaves as load stealing power. The setup was connected such that the source monitors all the three loads. In a practical system, each load can be treated as a domestic load and the source is the end transformer of the distribution system supplying the domestic loads. The connection was carefully made and verified before the system was switched ON for the testing of the algorithm which was simulated earlier.

In ideal case, when there is no power theft; source power should be equal to the sum of the load powers and the losses, as given by Equation 5.1

$$P_{source} = P_{load} + P_{losses} \tag{5.1}$$

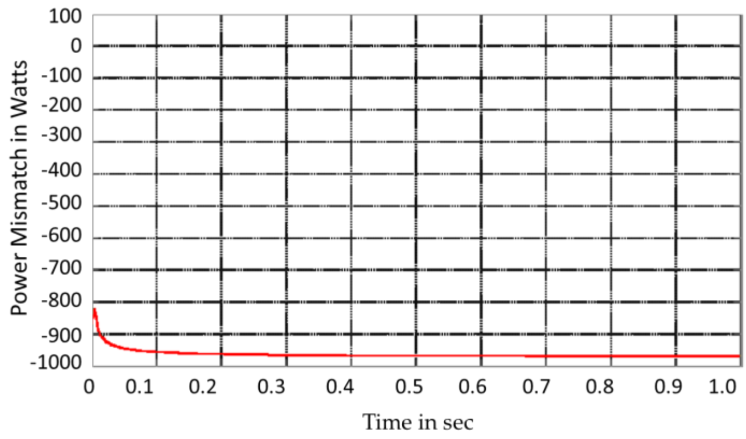

Figure 5.4: Power mismatch in case of lossy line with power theft

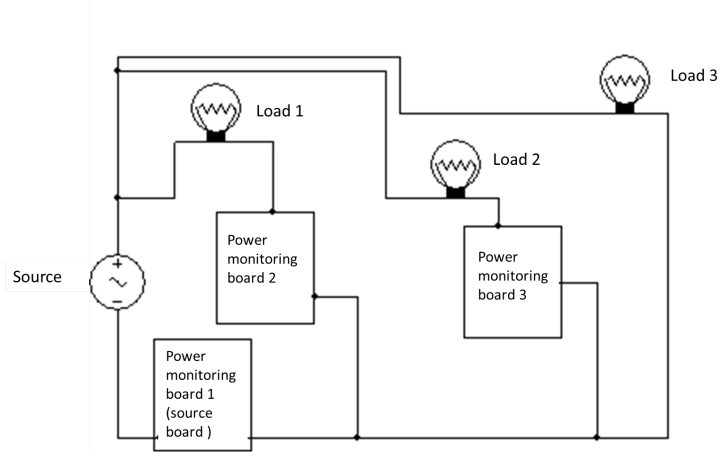

Figure 5.5: The setup for the implementation of power theft detection and connection of loads and the source along with the power monitoring modules

The setup of the system with the connections can be seen in Figs 5.6 and 5.7 where the boards, loads, and the communication modules are marked.

The Fig 5.8 shows a screenshot of the power monitoring GUI showing the results of the case of no power theft. The power monitoring modules were connected to different ADC channels of the MDA 300 as each board had a different calibration equation.

The connections for the setup were as follows:
Source node : Node 7, ADC 0 (Sum of powers of all the loads connected to the source)
Load 1 : Node 8, ADC 1 (Load connected was 100 watts)
Load 2 : Node 9, ADC 2 (Load connected was 60 watts)

It can clearly be observed from Fig 5.8 the power at the source is 156.79 watts (node 7, ADC0).

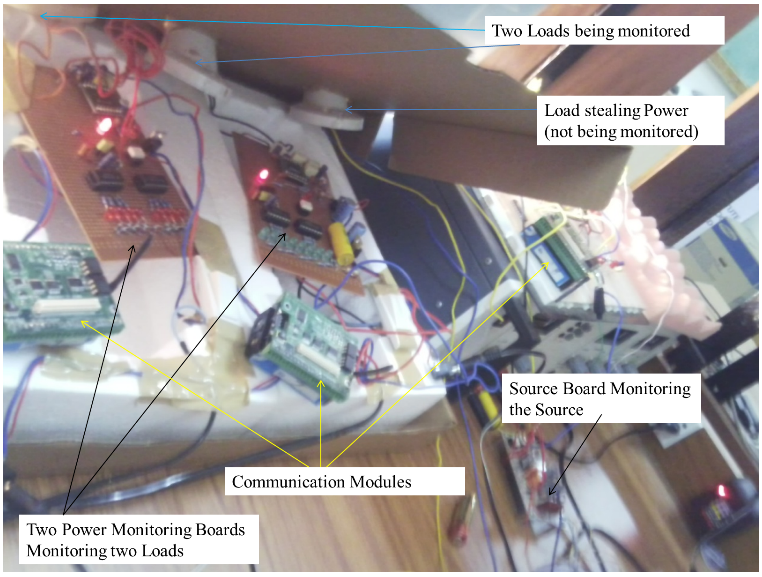

Figure 5.6: The setup of the system with the source and the three loads and three nodes

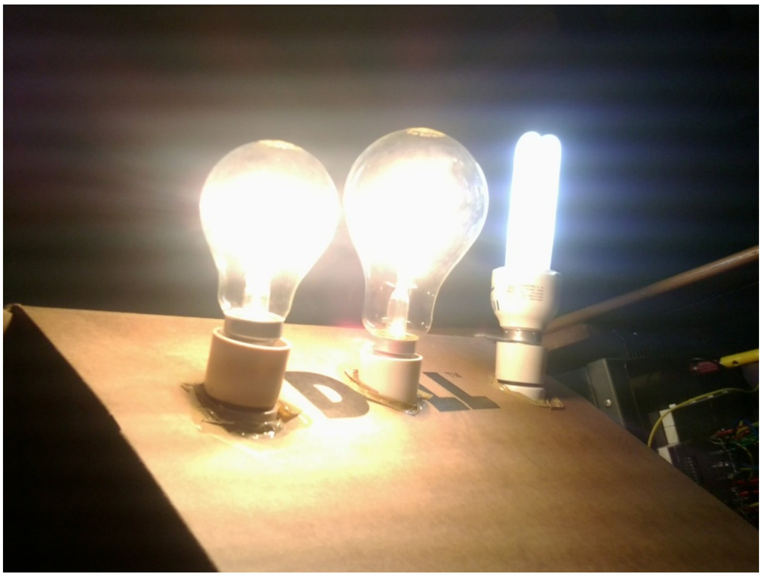

Figure 5.7: Three random loads of which two are monitored loads and one is the load stealing power

The actual power at the source was 160 watts which is the sum of the two monitored loads of 100 watts and 60 watts. It can also be seen that the Load 1 connected to node 8 and ADC 1 reads 99.41 watts; the actual load connected to this node was of 100 watts. Also, the load connected to node 9, ADC 2 was Load 2 that is measured to be 62.06 watts whereas the actual load connected was 60 watts. The power mismatch between the loads and the source is 4.68 watts which is negligible and hence it can be deduced that there is no power theft.

Fig 5.9 shows the results of the system under the case of power theft. The system is monitoring

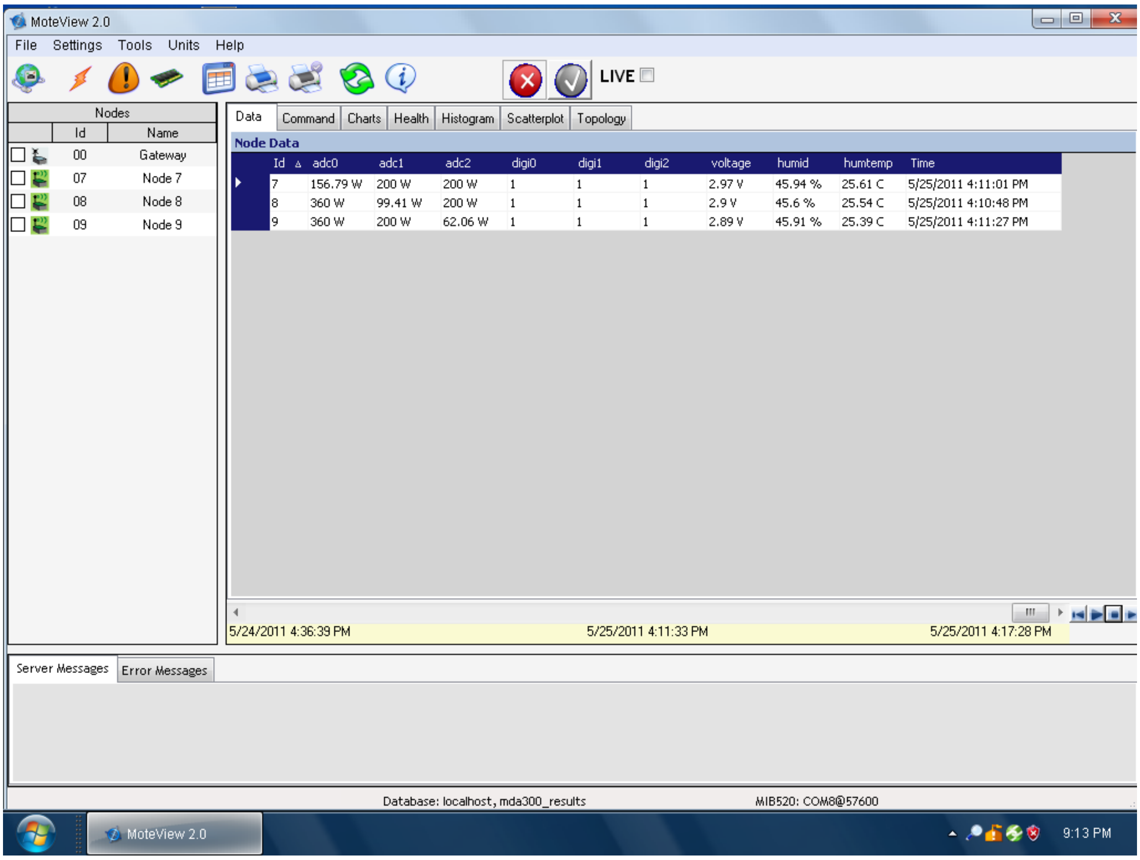

Figure 5.8: A screenshot of the Moteview software monitoring loads for the case of no power theft

two loads and a source. The third load is also connected to the source but is not monitored. The third load that is not monitored is the load stealing power from the source. The results show us the source power was 360 watts. The monitored loads were kept the same again i.e., 100 watts and 60 watts, the reading of which are measured to be 98.09 watts and 59 watts respectively. The power mismatch in this case is 202.91 watts which is a significant loss for the loads connected in the system. The actual theft load connected was 200 watts. Therefore, the power being stolen can be found out clearly calculated by the developed system.

Therefore, from the power theft detection system, the results obtained can be summarized as follows:

In case of no power theft,

$$P_{Source} = 156.79 \text{ watts}$$
$$P_{Load1} = 99.41 \text{ watts}$$
$$P_{Load2} = 62.06 \text{ watts}$$
$$\text{Power mismatch} = 4.68 \text{ watts (No theft)}$$

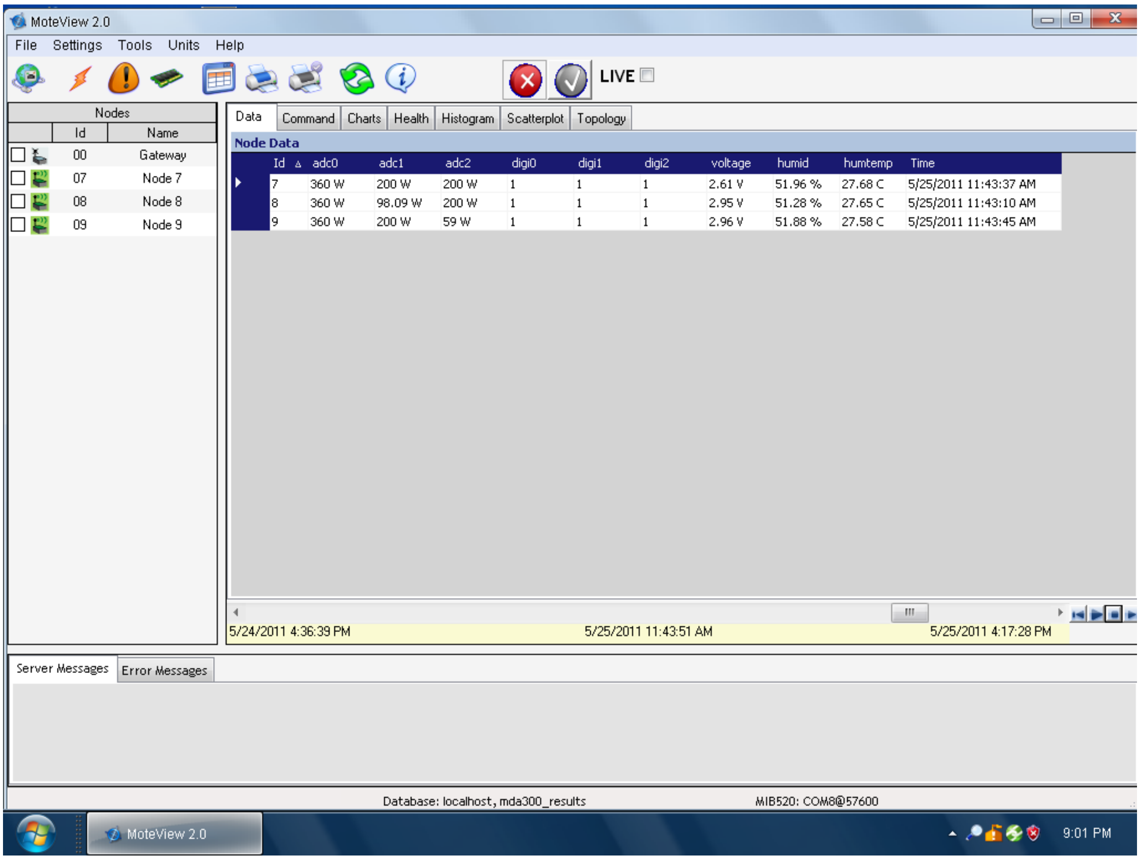

Figure 5.9: A screenshot of the Moteview software monitoring loads for the case of power theft

In case of power theft,

$$P_{Source} = 360 \text{ watts}$$
$$P_{Load1} = 98.09 \text{ watts}$$
$$P_{Load2} = 59 \text{ watts}$$
$$\text{Power mismatch} = 202.91 \text{ watts (Theft of 200 watts)}$$

From the above experiments, it is very clear that the proposed power monitoring system can be efficiently used for the power theft detection application in distribution systems.

5.2 Other Applications of the WSN Based Power Monitoring System

The WSN based power monitoring system is a very useful tool to monitor the power consumption by various loads individually or in a group. A group of loads connected to a single source can be monitored efficiently by using the proposed WSN based power monitoring module. Some of the other applications are as follows.

- The WSN based power monitoring module can be extended for the monitoring of the complete power distribution system. The system can be further developed to monitor the overloading, over voltages and over currents in the system by interfacing a few sensors with appropriate additional circuitry. The overloading of the transformers is a usual problem in the distribution system these days which can be monitored in a very effective manner by using the system developed. Not only the overloading current but also the temperature of the oil in the distribution transformer can be monitored by using suitable sensors connected to the communication module along with the power monitoring module. Essentially the electrical power distribution system being a three phase system, a three phase power monitoring module can be designed on the similar lines of the single phase power monitoring system developed in the present work.
- The power monitoring concept implemented using high bandwidth communication technology like WiMAX can be used for the monitoring of smart grids. Smart grids are a very new and fast emerging technology in power systems. The WiMAX has a high bandwidth enough so that the speeds can get as close to the speeds of optical fibre communication for fast transfer of data sufficient for the monitoring of smart grids. A typical smart grid is shown in Fig 5.10. With two-way communication combined with a high bandwidth, some control actions can be attempted in smart grids which do not require very high speeds.
- The WSN based power monitoring module can be used in smart home applications to monitor the power consumption in different parts of the home and thereby take suitable control actions based on the requirement. The smart home applications are being developed on a large-scale and the WSN based power monitoring module can be an integral part of the smart home applications.

5.3 Summary

In this chapter a novel application of power theft detection using the WSN based power monitoring module was discussed. The implementation of the power theft detection algorithm gave a proof of concept for the algorithm. This chapter also discusses the applications and further scope of work that can be done with the WSN based power monitoring module.

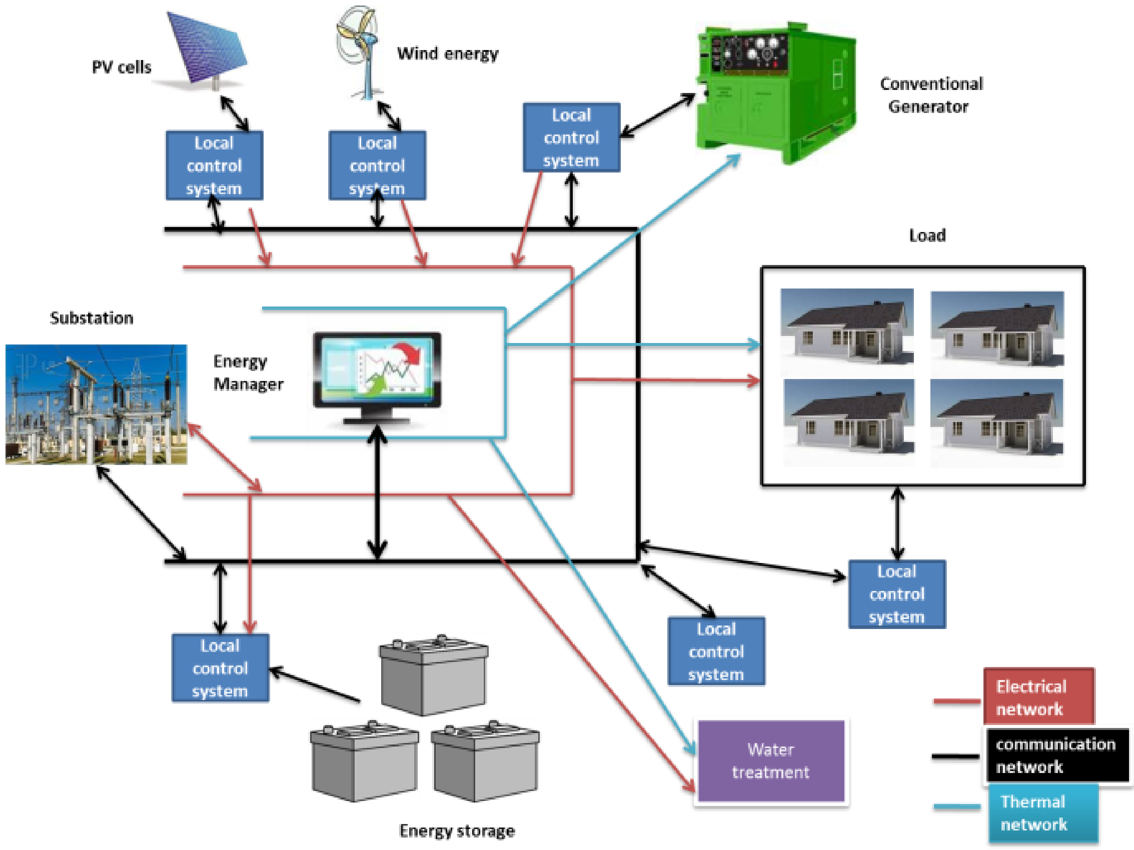

Figure 5.10: A schematic representation of a smart grid

Conclusions

In this project, architecture for power monitoring system using the wireless sensor network technology is proposed, designed, developed and tested. A Multi-hop mesh network was set up for long range and reliable wireless communication using the IRIS motes. A prototype for power sensing module was designed and developed for monitoring a single phase system. The hardware developed for single phase power monitoring has ADE 7577 energy metering IC as the power computing unit. The sensing module is calibrated and tested for the accuracy. The experimentation performed shows that the measured power almost matches the rated power. The calibrated sensing module along with the WSN node communicated the monitored power value to base/sink at periodic intervals. With appropriate scaling this model can be extended to distribution systems also. To eliminate the constraint of the distance in the wireless networks, the communication module (IRIS) was replaced with an 8051 microcontroller based GSM transceiver to compute the power and transmit it to server.

It is clear from the experimentations that the wireless sensor networks can be successfully employed to smart grids for monitoring purpose. With proper design it is shown that WSN can be employed to mitigate power theft and can be effectively used for monitoring the voltages, currents and powers. For large scale deployment, cost effective power monitoring system is essential, which requires a reliable and low cost WSN mote design. This system can be extended for many other applications like smart home automation, online billing and smart metering applications also. This can also be further extended for complete distribution system monitoring with the monitoring of transformers' temperature, oil levels, over-loading, etc.

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