ADAPTIVE THERMAL COMFORT COMPUTATION WITH ZIGBEE WIRELESS SENSOR NETWORKS

A THESIS IN

Electrical Engineering

Presented to the Faculty of the University
of Missouri-Kansas City in partial fulfillment of
the requirements for the degree

MASTERS OF SCIENCE

BY,

KRISHNASWAROOP ASWATHANARAYANAJOIS

B.E., Visvesvaraya Technological University, India, 2009

Kansas City, Missouri

2013

ADAPTIVE THERMAL COMFORT COMPUTATION WITH ZIGBEE WIRELESS SENSOR NETWORKS

KRISHNASWAROOP ASWATHANARAYANAJOIS, Candidate for the Master of Science Degree

University of Missouri-Kansas City, 2013

ABSTRACT

The rapid development of wireless communications, scalable technology enabling large scale mass production of System-On-Chip boards, and low cost and low power sensors have made wireless sensor networks easy accessible and usable. Zigbee (802.15.4) operated wireless sensor networks have been commonly used in home automation, building automation, personal health care and fitness, consumer electronics, telecom services etc.

In our thesis we investigate Zigbee's application in computing thermal comfort in indoor environments as an extension of home automation systems. Maintenance of thermal comfort consumes a large majority of energy costs. In our home automation system we interfaced a Honeywell based humidity sensor. The Zigbee system consists of a central unit called a coordinator which acts as a control unit. The coordinator is responsible for configuring the network and the start of the network. The end-devices which also act as routers are interfaced with a humidity sensor, an inbuilt temperature sensor, light sensor and accelerometer. The end-device periodically reports data like temperature, humidity, light and accelerometer readings. From these readings, a thermal comfort index is calculated by an index called Predicted Mean Vote. Thermal comfort is dependent on variation of 6 factors like clothing, Metabolism, air temperature, air velocity, mean radiant temperature and relative humidity. A series of simulations are performed with MATLAB to illustrate variation of PMV with the above mentioned 6 factors. Finally prediction and opinion is given about cost variation with energy usage variation. Also the thesis gives advice on achieving thermal comfort by taking into consideration different factors and also to change those factors to achieve thermal comfort at expense of the cost.

APPROVAL

The faculty listed below, appointed by the Dean of the School of Computing and engineering, have examined a thesis titled "Adaptive Thermal Comfort Computation with Zigbee Wireless Sensor Networks " by Krishnaswaroop Aswathanarayanajois, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

Supervisory Committee

Cory Beard, Ph.D., Committee Chair
Department of Computer Science & Electrical Engineering

Vijay Kumar, Ph.D.
Department of Computer Science & Electrical Engineering

Yang (Cindy) Yi, Ph.D.
Department of Computer Science & Electrical Engineering

Table of Contents

LIST OF ILLUSTRATIONS

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and thank my advisor Dr. Cory Beard for giving me an opportunity to work under him. His support and advice throughout my thesis project has been invaluable in completing my work successfully.

I would like to thank my committee members Dr. Vijay Kumar and Dr. Yang(Cindy) Yi for their support and interest in my thesis.

I would like to thank my other faculty members Dr. Praveen Rao, Dr. Yugyung Lee for giving me an opportunity to work and contribute in E-save project.

I would like to thank my lab friend Chetan, as a good friend willing to help and give valuable suggestions. It would have been lonely without him. I would also like to thank my friends Teja Swaroop, Palgun Reddy, Abhinav Garlapati and Aadit Modi for their valuable comments and suggestions.

Finally I would like to thank my parents Mrs. Geetha and Mr. Ashwathanarayana G, my dearest brother Dr. Abhiram , my uncle Sathyanarayana G , aunt and my cousin and all my family members who helped me in various stages to complete my work and support throughout the years they offered me here in graduate school.

CHAPTER 1

INTRODUCTION

1.1 Thermal Comfort

In general comfort is something means soothing or consolation. A person may be comfortable when he is associated with things that bring him pleasant feelings in his minds. Associating himself with familiar objects, eating foods which he is familiar with doing things he likes etc. will create all positive effects on his mind and a sense of comfort starts to show up in his body. We can say comfort is a psychological sense. Thermal comfort is evaluation of comfort related to person in a living room or closed arena with different factors. As per ASHRAE-55, thermal comfort is defined as the mind condition. It is basically satisfaction expressed by human beings. The mind satisfaction is through subjective evaluation. Thermal comfort is evaluated by different factors. Before gazing at what would be ideal thermal comfort design for comfortable living we should think where our lives are heading in future when we are focused on cost cutting and utilities. Human conditions may become worse in the future due to globalization and ecological imbalance. Humans have very good adaptability to different climatic conditions. But exposing humans to artificial environments have decreased their capability of adaptability and limited their survival. So for humans to be productive and healthy a balance is to be achieved between acclimatization and minimization of physiological response.

1.2 Literature Survey on Sensor Networks

Wireless sensor networks have been used in a plethora of applications. Scaling of technology, advancement in micromechanical systems, small microcontrollers and microprocessors, and low power radios have created multi-functional sensor devices.

These devices have low power consumption and are used in various applications. These devices can be networked over a wireless medium and utilized in many applications with a wide variety of functions. Wireless sensor network devices are incorporated with a radio transceiver and a set of transducers. The basic function is to acquire information about our surrounding environments. Sensor networks can be deployed in large quantities, they can organize themselves as adhoc multihop networks communicating and sending information in the form of packets to sink nodes. Sink nodes are mostly attached to PC's collecting data. Sensor networks have been in used in diverse fields including inventory, intrusion detection, motion tracking, toys, environment, medicine, machine malfunction, agriculture, military, monitoring, and many others.

In the medical field sensor networks have been used remotely and in an unnoticed manner in monitoring patients' blood pressure, heart beat, and the hospital is alerted when some parameters are changed or altered.

In agriculture, wireless sensor networks have been used to sense agricultural parameters like soil moisture, humidity, rainfall etc. A WSN provides insight for farmers in Irrigation management, amount of water required by each crop, thus reducing cost and improving quality of the end product.

A pollution detection system using wireless sensor networks detects different levels of pollution in a city, town, river etc.

The Military has widespread use of wireless sensor networks. They find use of wireless sensor networks in some common military applications like troop detection behind enemy lines; enemy intrusion detection, collecting geographical information at the deployed areas, force protection etc.

Smart home monitoring is another widespread application of wireless sensor networks.

In this thesis we use wireless sensor networks with the Zigbee wireless protocol. The IEEE standard 802.15 is a wireless networking standard for personal area networks. The group 802.15 mainly addresses operability of portable and mobile computing devices like cell phones, pagers, PDA's and also consumer electronic devices. IEEE 802.15.4 is a wireless standard for specifying low rate personal area networks. This group is responsible for providing physical and MAC layer specification for personal area networks. Zigbee is a wireless standard for high level communication personal area networks. Zigbee devices are usually built with low power radios and a microcontroller unit. This sensor network implements the Zigbee 802.15.4 wireless standard in transferring data from a source node to sink node. Zigbee wireless sensors have plenty of applications. Some of the common applications for the Zigbee Wireless sensor network include home automation, automation of buildings, patient data collection in medical fields, smoke alarming systems, intruder alarming systems, and temperature control. Other applications include smart lighting, sensing applications with motes called Telsob and Micaz and also in safety and security systems. Zigbee Wireless sensor networks have been used in systems to measure energy consumption as well as compute thermal comfort in the home environment. The authors of [1] propose energy-saving Zigbee based architecture for room. The idea of the paper with this architecture is to reduce standby power consumption and make a room controllable with IR remote control of a home appliance.

The proposed architecture by the authors in [2] describes an efficient energy management system. The architecture reduces power consumption in the home area when implemented. The room consists of power outlets, a light and Zigbee hub. An IR based home appliance remote controller is used to control the entire room. The Zigbee hub comes with an IR code learning function and educates the IR remote control signal about the appliance connected to the power outlet. The Zigbee hub communicates with home server and reports power consumption. A thesis entitled "Design of a wireless platform for wearable and home automation applications" illustrates a Zigbee based system that can be used in homes to compute energy consumption by individual devices like Microwave oven, printer etc. The authors in [4] illustrated thermal comfort model with Zigbee wireless sensor networks. They proposed a CMAC (Cerebellar Model Articulation Controller) based model in a smart home to evaluate a Predicted mean vote (PMV) and compute thermal comfort. The authors of [5] propose an artificial light powered sensor network. The goal of this sensor network is to measure thermal comfort with wireless power transfer and wireless data communications. The constructed sensor node has a microprocessor, IC-temperature sensor, a radiation thermometer, humidity sensor, a micro machined flow sensor to calculate PMV.

1.3 Summary of Contributions

This thesis is a part of research work carried out by the E-Save group at UMKC. The aim of the E-save group is develop smart energy solutions for people to experience a smart life. The other goals are to promote and give information for wise energy use across different communities. Our part of the work seeks to give people tools to understand and efficiently use energy to maintain thermal comfort. It uses a factor called PMV (predicted mean vote). Also the thesis emphasizes giving cost prediction and understanding of how energy saving influences cost using home area networks. To compute humidity, humidity sensor was attached to the Zigbee board. Humidity was computed in compliance with humidity of surroundings.

1.4 Plan of Work

The main underlying principles of thermal comfort are described in Chapter 2. Chapter 3 will focus on the thermal comfort index. We chose to study predicted mean vote, described in detail. Chapter 4 will focus on Zigbee wireless sensor networks. Chapter 5 gives insight into the Zigbee model description for computing thermal comfort. Chapter 6 describes experimental set up with live data collected from humidity sensor and results of MATLAB simulation for computing PMV. Chapter 7 also discusses relative costs for maintaining thermal comfort using various types of heating, ventilating and air conditioning equipment. Chapter 8 discusses briefly about conclusionS and future work.

CHAPTER 2

BACKGROUND

2.1 Factors Affecting Thermal Comfort

Thermal comfort, as discussed in Chapter 1 is a subjective matter and is mainly influenced by 6 factors. The factors affecting thermal comfort are classified into 2 categories .They are

1. Personal factors: Factors dependent on the occupants
   - Metabolism
   - Clothing Insulation
2. Environmental factors: Conditions of thermal environment
   - Air temperature
   - Relative humidity
   - Air movement
   - Humidity

2.1.1 Personal factors influencing Thermal Comfort.

2.1.1.1 Metabolism

Metabolism is an important factor that influences the thermal comfort. Metabolism involves chemical transformation inside the cells of a living organism. The catalytic enzyme metabolism allows an organism to grow, reproduce and maintain its structures and respond to environments. In thermal comfort jargon to describe metabolism associated with human beings, there are two types, basal metabolism that happens without consciousness and muscular metabolism with consciousness. Basal metabolism is also called biological metabolism. The second type of metabolism i.e. muscular metabolism involves muscular work. As a result of metabolism heat is generated inside the body. The heat generated inside the body may be dissipated to the environment. The heat may dissipate in form radiation, convection or conduction.

Table 1 describes the metabolic rates of different activities [6].

Table 1: Metabolic rates on different activities

Activity	Met	W/m^2	W(av)
Sleeping	0.7	40	70
Reclining, lying in bed	0.8	46	80
Seated, at rest	1.0	58	100
standing, sedentary work	1.2	70	120
very light work (shopping, cooking, light industry)	1.6	93	160
medium light work (house~, machine tool ~)	2.0	116	200
steady medium work (jackhammer, social dancing)	3.0	175	300
heavy work (sawing, planning by hand, tennis) up to	6.0	350	600
very heavy work (squash, furnace work) up to	7.0	410	700

Metabolic rates are expressed as power density, per unit body surface (W/m^2), the power itself for an average person (W) or in a unit devised for thermal comfort studies, called the "**met**". Deep down the body temperature measured is about 37°C. Skin is one of the sensing parts in the human body of the 5 available sensory mechanisms. It has two heat sensing organs. The outward heat flow from the body to objects at lower temperature is sensed by one part of skin. The other set of skin sensors respond to inflow of the heat to the body. The sense organs on the skin detecting heat flow outward from the body are located close to skin's surface, found in nose, bends of elbow and also on finger tips. The inward flow sensing organs are located deeper in the skin and are concentrated on upper lips, chin, nose, upper chest and forehead. The blood circulation through the skin is controlled by the sensory responses triggered by both sets of skin sensing organs. The human body has its own source of thermal heating. Metabolic activity in the human body generates thermal heat and is able to adapt to wide range of environmental conditions.

The hypothalamus is a gland at the base of the brain just above the pituitary gland. It is the region of body's thermostat. This thermostat is maintained at a temperature of 98.6°F (37°C). Its function is to monitor changes in blood temperature caused by internal body thermal conditions and also change of temperature across the skin. When the body temperature change is detected by the hypothalamus is less than the set point, a physiological response is initiated to increase the temperature. In case of a warmer body, the physiological response is initiated to decrease the temperature. In this way, the body attempts to maintain its thermal equilibrium or heat balance, resulting in thermal comfort. The metabolic activity rates described in the table are used in the PMV index to compute thermal comfort. Hence metabolic activity forms an important factor.

2.1.1.2 Clothing Insulation

Clothing is the second important factor that influences thermal comfort. Clothing determines how much heat is dissipated to the environment from the body. For a normal human being living on earth depending on seasons and place the clothing sense varies. For example for a person from tropical country like India where temperature is relatively high, people are used to warm and hot climate and dress according to climate. People in countries of Europe and North America are used more of a temperate climate. Layers of clothing may vary because of geographical differences and climate. Depending on loss of heat, thermal balance is affected for a person. Clothing is expressed in terms of a unit called "**Clo**" for the purpose of measuring thermal comfort. 1 **clo** corresponds to insulating cover over a whole body. It also corresponds to a resistance of 0.155 m^2w/K. According to ASHRAE-55[7] one **clo** is equivalent to keeping a resting person warm in a windless environment at 21.1°C (70°F). Table 2 indicates insulating values for different clothing attires.

Table 2: Insulating values for different clothing Attires.

Clothing	clo	m^2 k/w
Naked	0	0
Shorts	0.1	0.016
Typical tropical unit	0.3	0.047
Light Summer clothing	0.5	0.078
Working clothes	0.8	0.124
Winter Indoor clothing	1	0.155
Traditional Business suit	1.5	0.233

2.1.2 Environmental factors affecting thermal comfort

As we already know, thermal comfort is also affected by 4 important environmental factors.

2.1.2.1 Air Temperature

Average temperature of the air surrounding an occupant (person) with respect to location and time is called air temperature. Air temperature can be measured with a wet bulb thermometer or dry bulb thermometer. Wet bulb temperature is measured with an ordinary thermometer but cloth covered. So the thermometer measures reduced amount of moisture in air because cloth absorbs and gives out some heat. Thermal comfort uses Dry-bulb temperature to measure air temperature. ASHRAE-55[7] defines air temperature measured to be average of head, waist and ankle levels. It is usually measured in Fahrenheit or Degree Celsius. Exposing an ordinary thermometer to atmosphere indicates dry-bulb temperature which is also called atmospheric temperature. Dry-bulb temperature indicates amount of heat in the air and its average kinetic energy of air-molecules. The amount of air-moisture is not indicated by Dry-bulb temperature. According to [6] dry-bulb temperature forms important climate variables for human comfort and building energy efficiency.

2.1.2.2 Relative Humidity

Before understanding relative humidity let us know about absolute humidity. “Absolute humidity is defined as ratio of mass of water vapor to mass of dry air in a volume of air at given temperature” as per [19]. In terms of absolute humidity, relative humidity is defined as ratio of absolute humidity to highest possible absolute humidity. 100% relative humidity means air is holding (saturated) 100% of water vapor and cannot hold anymore. “The amount of water vapor in air at any point of time is usually less than that required to saturate the air. The relative humidity is the percent of saturation humidity, generally calculated in relation to saturated vapor density.” [20]

Relative humidity = (Actual vapor density/ saturation vapor density)* 100 (1) [20]

Vapor density is measured in g/m^3. To illustrate with an example, Let us consider actual vapor density to be 10 g/m^3 at 20°C and saturation vapor density to be 17.3 g/m^3, then relative humidity is

$$RH = (10/17.3)*100 = 57.8\% \qquad (2)$$

To clarify what it means to define relative humidity, it is the amount of moisture in the air compared to what air can hold at that temperature. When the air can’t hold all moisture, it condenses as dew. Thermal comfort depends a lot on relative humidity. When we do lot of work or we run for some time or walk swiftly we tend to sweat. The skin relies on air to absorb moisture from our skin. When there is 100% relative humidity in air, it can’t absorb any water vapor from surroundings and people tend to feel hot. When air is having less relative humidity, air will be able to absorb moisture from surroundings and we tend to feel cooler. So by this simple example we see that relative humidity influences ones thermal comfort directly.

2.1.2.3 Air Movement or Air Velocity

Air movement is defined as the rate of movement of air in any direction at any point. ASHRAE -55[7] defines air velocity as the as the average speed to which a body is exposed. Air movement may provide desirable cooling in warm conditions. Air speed also remains a subjective as well as psychological matter because some people are comfortable under lower air speeds but some under higher air speeds. The feeling of pleasantness to unpleasantness for people based on air speeds is directly influenced by air speeds depending on other factors of thermal comfort like relative humidity, mean radiant temperature , clothing and metabolic rate.

When HVAC systems are designed, design engineers take into account a lot of factors that influence air movement through the building. ASHRAE [6] has standard guidelines in design of air speeds in such buildings for feeling comfortable. ASHRAE and other organizations emphasize factors like volume of air per unit time, percentage of outdoor air and typical duct size and location of outlets. Humans have a thermoregulatory system which maintains a constant temperature of about 98.6°F inside the body to feel comfortable at all times. This system regulates and controls heat transfer, release of metabolic heat by regulating skin temperature. Skin temperature is varied by variation in blood supply to the skin and sweating at the skin surface. Heat transfer at skin varies based on surface temperature and local air motion. In warm and hot-humid conditions, moisture on the skin has a strong effect on thermal sensation. Because heat loss, skin temperature, and thermal sensation are interdependent on local air motion, air motion is a factor to be considered in determining thermal comfort.

2.1.2.4 Radiant Temperature

In general mean radiant temperature is defined as heat radiated by any material. Radiant temperature mainly depends on the emissivity of material. The mean radiant temperature is one of the meteorological parameter's governing the human energy balance and thermal comfort. Mean radiant temperature cannot be measured directly. Various methodologies have been described to evaluate and calculate mean radiant temperature. The methods include either applying definition of mean radiant temperature and equations related to it or by using thermometers or sensors. Radiant temperature can be calculated by measuring temperature of surrounding walls and surfaces and their position with reference to the person. The angle between surfaces and person are calculated to know the impact of radiant fluxes on the person. Generally all of the surfaces are assumed to be black surfaces because of high emissivity. "Assuming the sum of the angle factors is unity, the fourth power of the MRT equals the fourth power of surrounding surface temperature" multiplied with respective angle factors of surfaces.

The following equation is used to measure mean radiant temperature [13].

$$MRT^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \ldots + T_n^4 F_{p-n} \qquad (3)$$

Here

MRT = Mean Radiant temperature

T_n = Temperature of surface "n" in Kelvins

F_{p-n} = angle factor between a person and surface "n"

"If relatively small temperature differences exist between the surfaces of the enclosure, the equation can be simplified to the following linear form"

$$T_r = T_1 F_{p-1} + T_2 F_{p-2} + \ldots + T_n F_{p-n} \qquad (4)$$

The difficulty in using either (3) or (4) is to determine angle factors. Position and orientation of a person influences in determining angle factors. As the number of surfaces increases or if the surfaces are of different shapes, complexity of calculating mean radiant temperature increases. Due to this reason mean radiant temperature can be determined by a particular thermometer.

Mean Radiant temperature is estimated through a black-globe thermometer. "The black-globe thermometer consists of a black globe in the center of which is placed a temperature sensor such as the bulb of a mercury thermometer, a thermocouple or a resistance probe. The mean radiant temperature depends on the diameter of the globe". So the globe can have any diameter but to be practically feasible the diameter is fixed at 0.15m.

The principles behind measuring mean radiant temperature using a globe thermometer are if the diameter of the globe is small, effect of air temperature and air velocity is greater thus accuracy of measuring mean radiant temperature is reduced. If the globe thermometer has external walls which are enclosed, the external globe surface absorbs radiation. A black matte paint of coating or electro-chemical coating is applied to the external surface of the bulb. By this principle we will know globe temperature and we can calculate mean radiant temperature. According to ISO the 7726 [14] standard the commonly used formula for calculating mean radiant temperature is in equation (5)

$$MRT = [(GT+273)^4 + (1.1*10^8* v_a^{0.6}/\varepsilon * D^{0.4})* (GT-T_a)]^{1/4} - 273 \quad (5)$$

Where

MRT = Mean radiant temperature (°C)

GT = Globe temperature (°C)

V_a = air velocity at the level of the globe (m/s)

ε = emissivity of the globe (no dimension)

D = diameter of the globe (m)

T_a = air temperature (°C)

Mean radiant temperature is an important factor to be considered in HVAC system to maintain thermal comfort inside the buildings. The comfort in buildings depends on air temperature and temperature of the surfaces. A reasonable way to maintain thermal comfort inside buildings is to have a balance between operative temperatures and mean radiant temperature which creates more comfortable space. This is accomplished with a effective building's interior design.

CHAPTER 3

THERMAL COMFORT INDEX

3.1 Introduction

We discussed in previous chapters factors that influence thermal comfort in detail. Based on those factors P.O Fanger is credited with introducing an Index for measuring thermal comfort. He is also credited with standardizing the thermal comfort index PMV for indoor environment. Fanger's thermal comfort model analysis indicated that thermal comfort was quite significantly affected by small changes in skin temperature and sweat temperature. By combining the information he had about skin temperature and sweat temperature, Fanger was able to deduce an equation for Predicted Mean Vote as a function of six variables: air temperature, mean radiant temperature, air velocity, air humidity, clothing resistance, and activity level. When combinations of parameters in the comfort equation satisfy we can easily say thermal comfort for a majority of individual is neutral. This model is widely accepted for measuring optimal thermal comfort.

3.2 Thermo-Regulatory System of Human Beings

Deep inside the body human being has a constant temperature of about 37°C. The internal temperature can be maintained constant if there is a balance between heat generated inside the body and heat dissipated to the environment. In humans, the hypothalamus region is responsible for controlling heat balance. Hypothalamus is part of brain that acts like a thermostat. Heat balance is maintained by information sent to this part of the brain about temperature conditions of the body. Thermo-receptors are mainly situated in skin, muscles, lungs and spinal-cords. These receptors are both cold as well as warm receptors. When temperature changes, these receptors are influenced and form nerve impulses information about temperature is transmitted to the brain. The brain coordinates body actions from received information resulting in maintaining body temperature constant.

Cold receptors start to feel cold if temperature in the skin decreases below a certain level and warm receptors start to feel warm if temperature in the skin increases beyond a certain level.

Metabolic activity continuously generates heat in a human body. Chemical energy is converted to heat. In hot environments excessive heat from the body is dissipated in form of sweat from the skin to maintain body temperature constant and in cold environments tension in muscles increases heat production. In even colder environments excessive muscles tension results in shivering generating 3 times the heat as compared to basal metabolism. If actual muscles are put to work (like lifting heavy weight, running, rigorous exercise etc.) the amount of heat generated will 10 times more than what is generated by basal metabolism. Heat from the deep core of the body is transferred to the skin by blood flow as well as through process of conduction to tissues.

Vaso-constriction is a phenomenon in which blood vessels contract especially in cold environments due to nerve impulses from the cold receptors. This results in reduced blood flow and also lowering heat flow to the skin. To maintain temperature of 37°C in vital parts of the body blood flow is reduced to feet and hands which start experiencing cold sensation.

In hot environments the temperature of the skin is high and temperature gradient is small between skin and surface and body. So there is less heat flow from core to skin surface. In warm environments blood flow is increased due to vaso-dilation. Vaso-dilation is a process in which blood vessels open up and heat flow is increased to the skin surface of the body. The increased heat flow to the skin is lost to the environment by sweating. The sweat production is also controlled by hypothalamus region of the brain.

The above mentioned phenomenon of vaso-constriction and vaso-dilation in cold and hot environments respectively attempt to maintain body temperature constant within certain limits. But core temperature of the body varies by small amount of 1°C (i.e. 36°C - 38°C) depending on the individuals.

When muscular work is done heat produces inside the body increases depending on the amount of work. The body core temperature is maintained to be constant. But body heat capacity and sweat capacity is limited and upper limit and lower limit exist for maintaining heat balance.

If ambient temperature rises above upper limits of regulated heat production environments, heat will be accumulated inside the body and core temperature increases. Blood flow to skin increases and new levels of heat may be reached with increasing core temperature. If the environments temperature is too high, core temperature keeps on increasing and at temperature of 42°C and 43°C will be fatal.

In cold environments heat loss happens due to vaso-constriction and core-temperature will decrease. If core-temperature reaches 33°C shivering starts and 25°C of core-temperature will be fatal.

3.3 Predicted Mean Vote

The block diagram in Figure 1 indicates input parameters that take 6 factors as input; PMV is calculated on a 7 point scale. Thermal comfort is described by equation called PMV. The equation is function of all the 6 parameters described in previous chapter

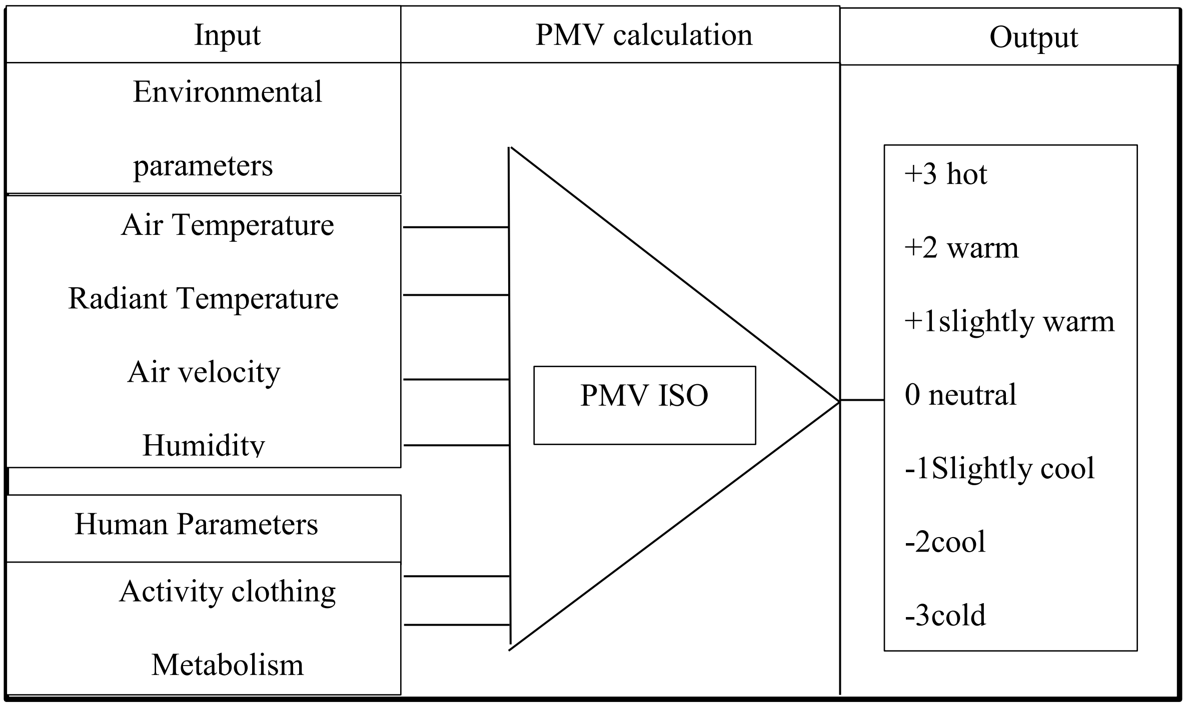

Figure 1: Thermal Sensation and PMV

$$\mathbf{A = (M - W) - 3.05 * 10^{-3}\{5733 - 6.99(M - W) - Pa\}} \quad (6)$$

$$\mathbf{B = 0.42\{(M - W) - 58.15\}} \quad (7)$$

$$\mathbf{C = 1.7 * 10^{-5} * M(5867 - Pa) + 0.0014 * M * (34 - Ta)} \quad (8)$$

$$\mathbf{D = 3.96 * 10^{-8} * fcl\{(tcl + 273)^4 - (tr + 273)^4\} + fcl * hc(tcl - ta)} \quad (9)$$

$$\mathbf{PMV = (0.303\, e^{-0.036M} + 0.028)[A - B - C - D]} \quad (10)$$

Where

PMV = Predicted Mean vote

M = Metabolism, W/m^2 (1 met =58.15 W/m^2)

W = External Work , in met.

I_{cl} = Thermal Resistance of Clothing, clo (1 clo = 0.155 m^2 K/W)

f_{cl} = The ratio of the surface area of the clothed body to the surface area of the nude body

ta = Air Temperature, °C

tr = the mean radiant temperature , °C

v_{ar} = Relative air velocity, m/s

Pa = Water vapor pressure, Pa

hc = Convective heat transfer coefficient, W/m^2 K

t_{cl} = Surface temperature of clothing , °C

Metabolisms for different activities are described in Table 1.

hc is defined by equation (11)

$$hc = \begin{cases} 2.38|tcl-ta|^{0.25} \text{ for } 2.38|tcl-ta|^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1\sqrt{var} \text{ for } 2.38|tcl-ta|^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \quad (11)$$

fcl is defined by equation (12)

$$fcl = \begin{cases} 1.00+0.2 * Icl \text{ for } Icl < 0.078 \\ 1.05+0.1 * Icl \text{ for } Icl > 0.078 \end{cases} \quad (12)$$

Before thermal comfort equation was introduced combined quantitative influence on all the parameters was not known until the equation.

PMV is measured on a 7 point scale and its range varying for +3 to -3.

Clothing temperature is given by formula below as

$Tcl = (35.7-0.028*(M -W)-Icl*(3.96*10^{-8}*fcl*((tcl+273)^4- (tr+273)^4) -fcl*hc*(tcl-ta)));$

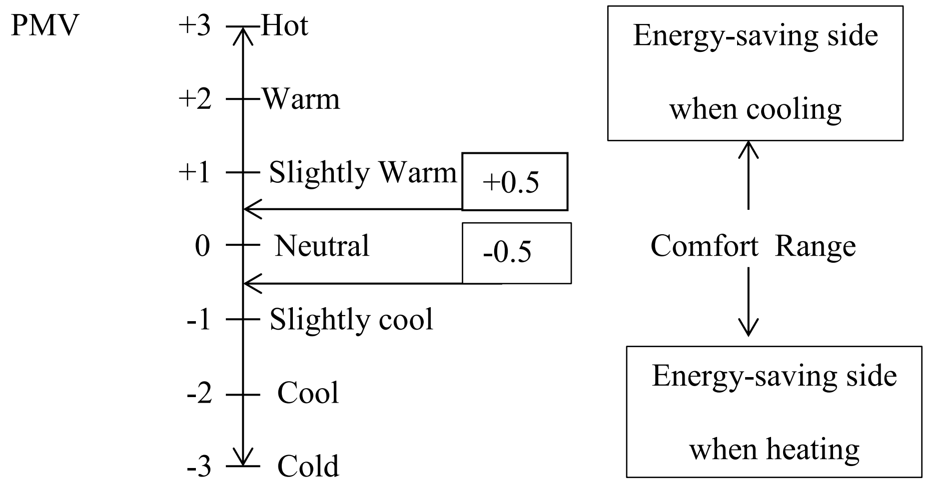

Figure 2: PMV on 7 point scale

The 7 point scale indicates mean response of a larger group of people according to the ASHRAE thermal sensation scale.

3.4 Percentage of Dissatisfaction

When a large group of people are exposed to same environment, the mean value of thermal comfort index is measured with the Predicted Mean Vote. The thermal comfort perception is subjective in nature and experience will be different between individuals. Among a large group of people in a common environment there will be a small percentage of people who are actually dissatisfied. The percentage of dissatisfaction among people is expressed as a function of PMV. Percentage of People Dissatisfaction is an index giving prediction about thermally dissatisfied people in percentage who feel either too cool or too warm. As a function of PMV the percentage of dissatisfaction is given by (13) as below and in Fig 3.

$$PPD = 100 - 95 * \exp(-0.03353 * PMV^4 - 0.217\,9 * PMV^2) \qquad (13)$$

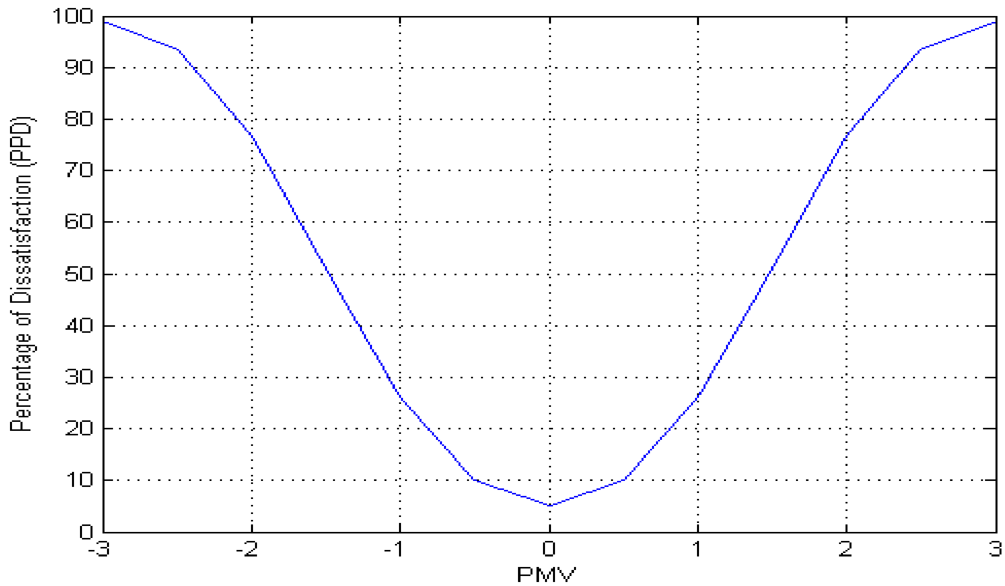

Figure 3: Variation of PPD w.r.t to PMV

CHAPTER 4

ZIGBEE WIRELESS SENSOR NETWORKS

4.1 Introduction to Zigbee

Zigbee is a low-power, low cost wireless networking standard [17]. The Zigbee technology is used in a wide range of products and applications across consumer, commercial, industry and government markets. A Zigbee wireless sensor network with interfaced humidity sensor was designed as a part of this research work. This section also describes Zigbee communication protocol standards, Zigbee devices used as part of the Zigbee sensor networks and packet formats used for communication. The Zigbee standard uses the ISM band (industrial, Scientific and medical radio bands) with 868MHz in Europe, 915 MHz in USA and Australia and 2.4GHz worldwide [21]. The Zigbee MAC and physical layer is built on IEEE 802.15.4 low cost Personal area networks. The Zigbee network layer supports star, tree and peer to peer network topologies. The application framework can be used by application programming interfaces using Zigbee networks.

4.2 Zigbee Devices

A Zigbee network has 3 logical devices:

1. Coordinator
2. Router
3. End-device

Usually a Zigbee sensor network will have one coordinator which will collect information from end-devices. Zigbee can have multiple end-devices and multiple routers.

Around a coordinator or a router the end devices are arranged in a star network helping the network to be low-cost. Multiple routers and coordinators can be arranged in a mesh network.

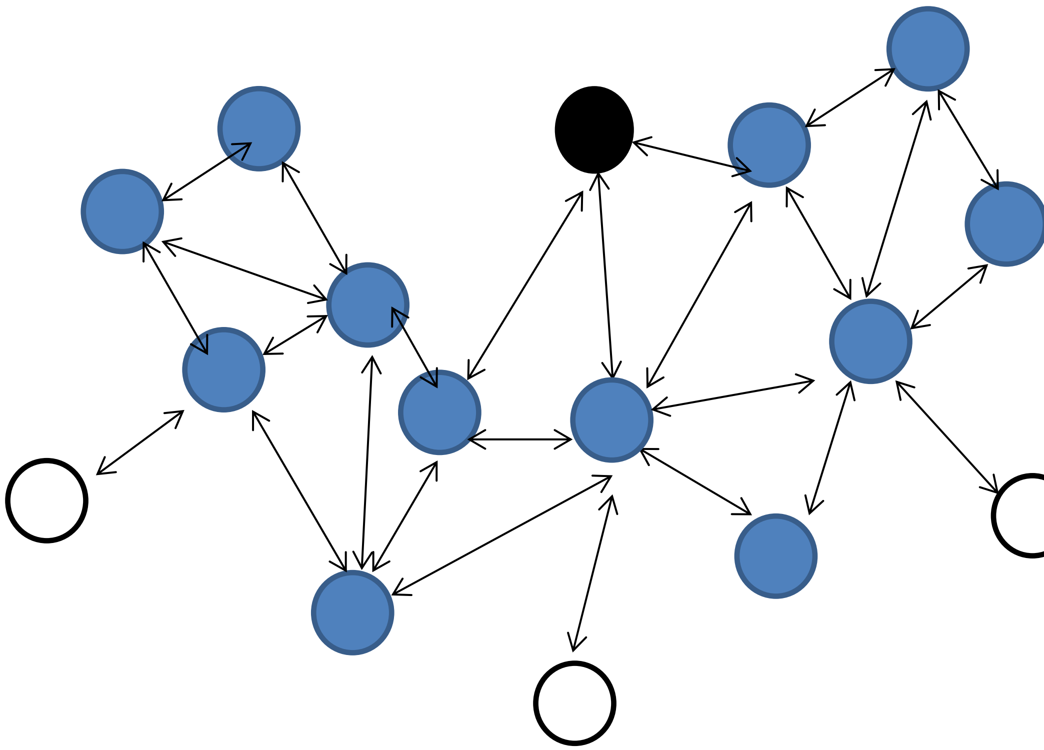

Figure 4: A ZigBee Network Cluster Tree of ZigBee Coordinator (black), the Routers (Blue), and the End Devices (white)

4.2.1 Coordinator

The Zigbee coordinator initiates the Zigbee network. It initiates the network by scanning for the existing network. Once the network is identified a channel is selected along with a network identifier or PAN ID. The main role of the Coordinator is starting up and configuring the network. Once this is done, the Coordinator behaves just like a Router node or can even be absent in the network later on. The network continues to operate regardless of the presence of the coordinator due the distributed nature of the ZigBee network. The coordinator can also act as a bridge for another Zigbee network.

4.2.2 Router

Routers also running application programs, act as intermediate devices transmitting data to coordinators by multi hop routing. They also should assist others in joining the network. Routers are to be active at all times in the network.

4.2.3 End-device

End-devices are usually battery powered sensor nodes running application programs. They only send information, but perform no routing functions.

4.3 Zigbee Protocol

The Zigbee physical layer supports three frequency bands. A 2450 MHz band with 16 channels, a 915 MHz band with 10 channels and 868 MHz band with 1 channel. All channels use direct sequence spread spectrum access mode. The 2450 MHz spectrum uses Offset Quadrature Phase Shift Keying (O-PSK) for modulation with a data rate of 250K bits/s per channel. The other two bands of 868/915 MHz use Binary Phase Shift Keying with a 915 MHz channel using a data rate of 40 K bits/s and 868 MHz is using a data rate of 20K bits/s. There are different characteristics of the Zigbee channel in the physical layer.

The Zigbee MAC layer uses Carrier Sense Multiple Access with collision avoidance (CSMA- CA) as a collision detection protocol to avoid collision in channels. Back off and reentry procedures are used to detect when an acknowledgement is not received in the network. While traditional MAC addresses are 48 bit in length, Zigbee based on IEEE 802.15.4 uses a 64 bit MAC address and 16 bit local address. These MAC address are allocated by IEEE. All ZigBee devices use 64-bit IEEE addresses by default.16 bit local address are used and assigned when a new device joins the network. However devices can be configured to use a 16-bit address only to reduce the communication overhead.

The Zigbee network layer is responsible for providing routing over a multihop network. Basically Zigbee identifies 3 types of devices. Section 4.2 identified 3 types in detail. The functionalities of the Zigbee network layer also include route discovery and maintenance, security and joining/leaving a network, with consequent short (16-bit) address assignment to newly joined devices.

Zigbee uses four frame structures in its protocol. One frame structure is for data, another as acknowledgement frame, one for peer entity control transfers and one for beacons.

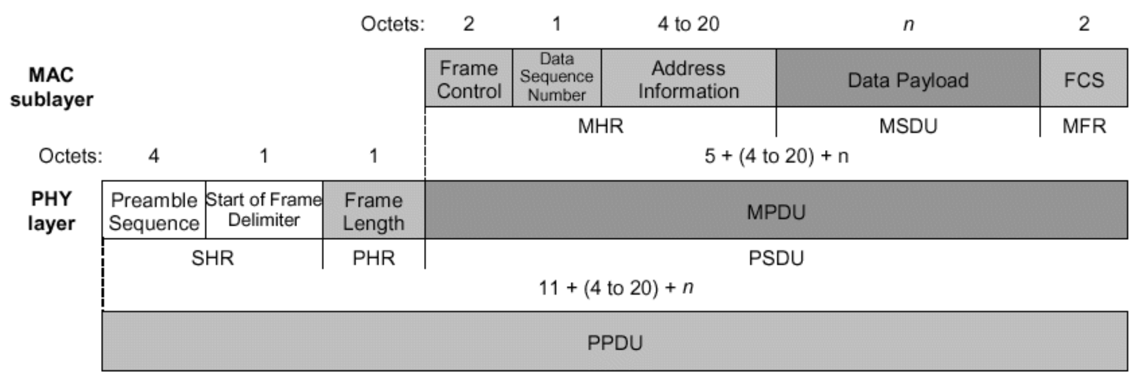

Figure 5: Zigbee Data frame

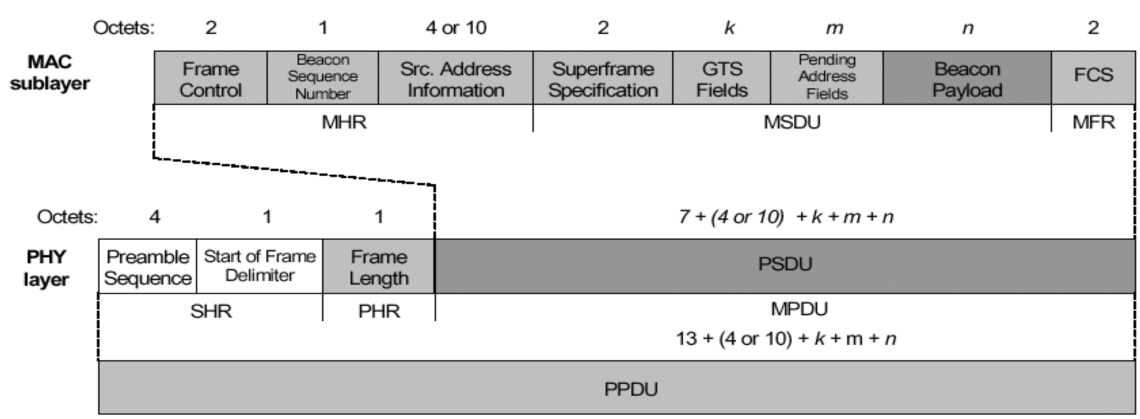

Figure 6: Beacon Data frame Zigbee

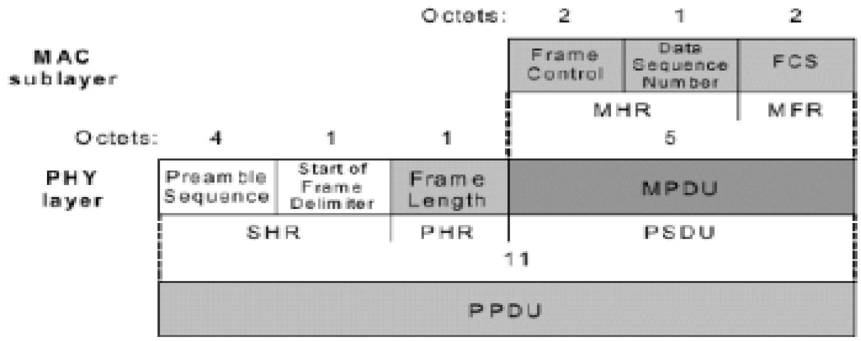

Figure 7: ZigBee Acknowledgment Frame

The packet reception is acknowledged by an 88 bit acknowledgement frame shown in Fig. 7. Once the data packet is transmitted and received in the network, acknowledgement is sent.

When a new node joins the network, the network should know that a new device has joined the network. The Zigbee coordinator transmits beacon frames in the network to mainly detect new devices joining the network and also to wake up a device when performing a function. Zigbee is a low-power wireless networking standard and beacons frames allow waking up devices when required and not all times thus ensuring low power consumption.

4.4 Zigbee CC2530znp Mini Kit

A Zigbee wireless sensor network interfaced with a humidity sensor was used to collect data for thermal comfort. The system consists of one device attached to a PC and multiple end device units. The end device continuously monitors temperature in Fahrenheit, light in lux, acceleration in 3 axes, and relative humidity. The whole system was designed with the Zigbee CC2530 Zigbee Mini kit from Texas Instruments. This kit was chosen because it provided ZigBee communication along with light, temperature, and accelerometer sensors on a single board at a low cost.

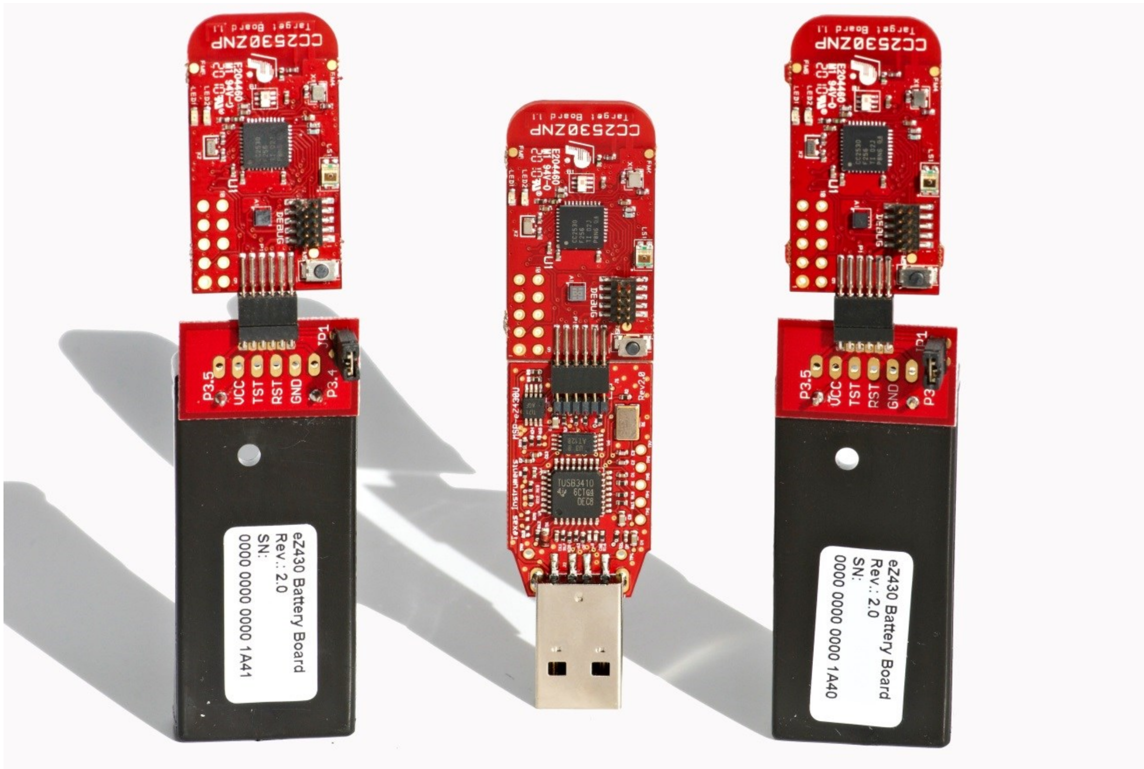

Figure 8:CC2530 mini kit

The Zigbee mini kit allows prototyping of simple Zigbee applications. The development kit has limited RAM and code size of the MSP430 on the ZNP-mini kit but is not intended to be used for ZigBee applications with profile support like ZigBee Smart Energy(SE) or ZigBee Home Automation(HA).

The CC2530ZNP mini kit is from TI (Texas Instruments) and use ZNP Zigbee Network Processor (ZNP) firmware and the CC2530 System on Chip module. The entire board hardware consists of an MSP430F2274 microcontroller and the CC2530Znp Zigbee radio. The MSP430 has an inbuilt temperature sensor. This controller is further interfaced with a light sensor, accelerometer, LED’s and input-output ports.

4.4.1 Coordinator

Figure 9 : Coordinator of CC2530ZNP mini kit

The coordinator as shown in Fig. 9 is a USB programming stick running a coordinator program powered by USB. It is also acts as a USB virtual serial interface. The serial interface is between PC and MSP430 directly. The USB stick is used as a debugger and programmer using the IAR embedded work bench.

4.4.2 End-device

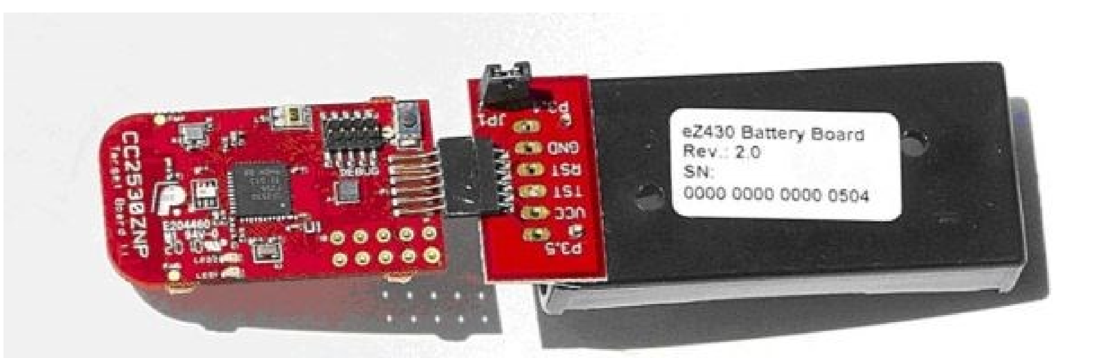

Figure 10: Battery powered End device

The battery powered device as shown in Fig 10 consists of CC2530ZNp System-On-Chip programmed and MSP430 application processor. The end-devices are required to report data such as temperature, light and movement along with humidity to the coordinator. Another feature of these devices is that they can be programmed as routing devices. This feature helps to extend Zigbee devices by routing messages from other end-devices. The hardware for coordinator, router and end-device are identical. Each target board can be programmed as coordinator or router or end-device.

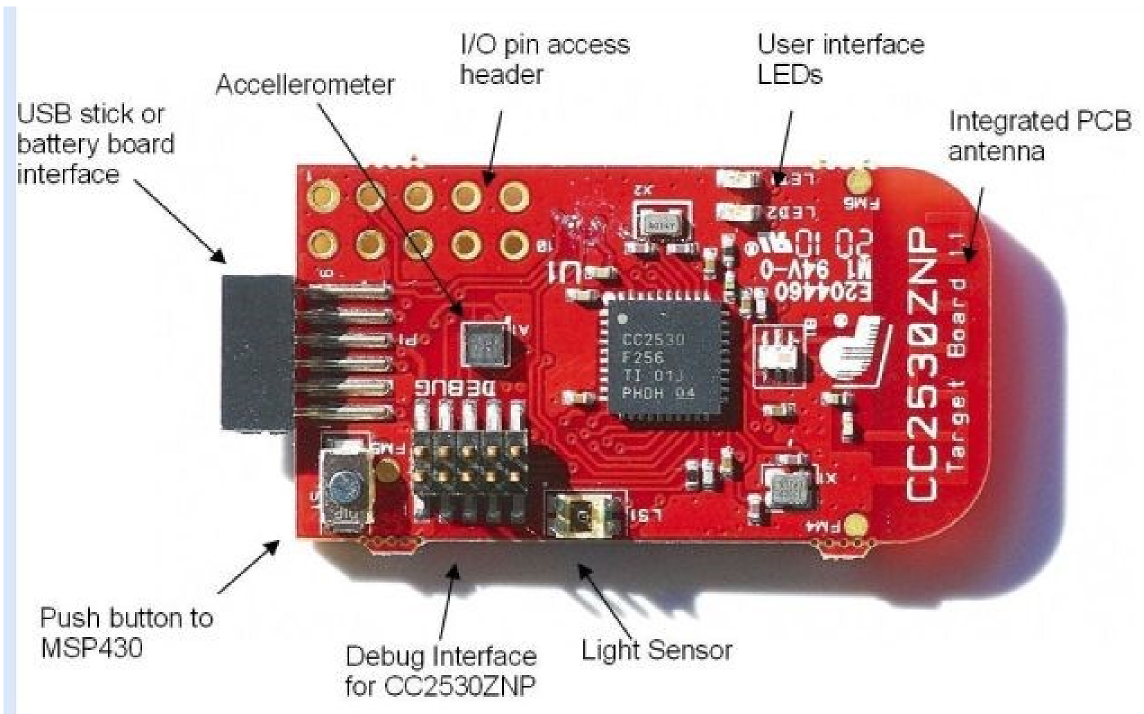

Figure 11: ZNP target board

4.5 Hardware Set Up

To interface coordinator to PC we need to install a hardware driver on the PC. The hardware driver was installed according to the instruction from [11]. On connecting the USB programmer to the USB port on a PC installed with these drivers, the device will be automatically detected as shown in Fig. 12. The driver can be found at the default location C:/Texas Instruments/CC2530ZNP Mini Kit/Drivers if not found automatically.

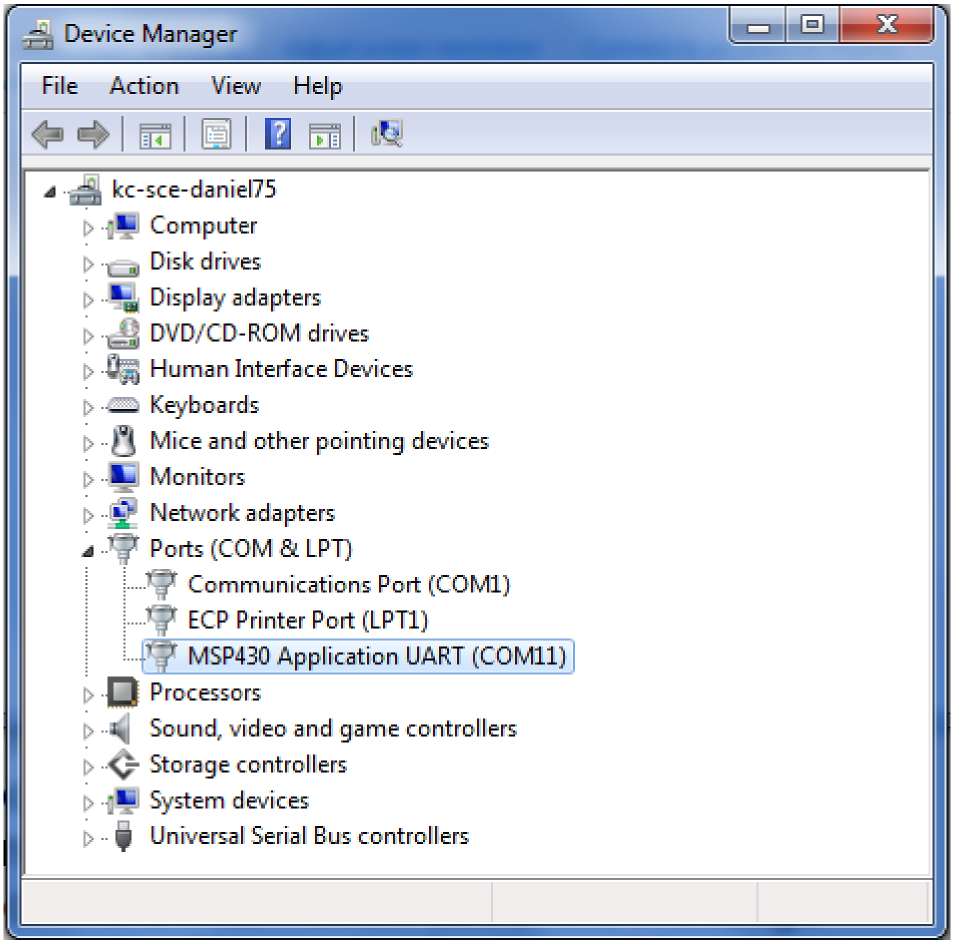

Figure 12 : The USB programmer listed in the device manager list

Using a virtual USB serial port, the ZigBee coordinator on the USB stick connects to the PC. Through a terminal program, the serial port interface can be accessed. By default HyperTerminal comes with the Windows OS and it can be found in the Windows Start menu/Accessories/Communication/Hyperterminal. On starting HyperTerminal, with a name given to the connection, the COM port used by the USB stick is selected. In accordance to the program the COM port properties are selected. Default properties are no flow control, 1 stop bit, 9600 baud, no parity, and 8 data bits as shown in Fig 13.

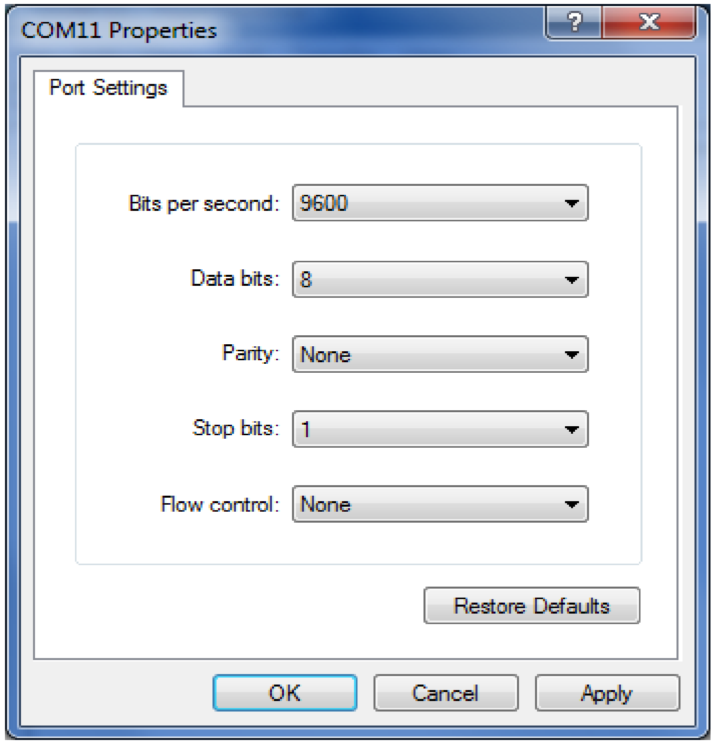

Figure 13: COM port settings

Once the batteries are inserted to one or more end devices, a jumper is connected at appropriate place and the end-devices are powered up. An activated end-device sends information to the coordinator in a packet format. The packets are sent in periodic intervals to the coordinator. When each end-device sends a green LED blinks indicating that a packet has been sent to the coordinator.

4.6 CC2530 Software Set Up

The IAR embedded work bench is used as a software IDE for programming the MSP430 and CC2530ZNP modules. The Zigbee end-device periodically sends sensor data on the start up with a sleep in between transmissions. Each Zigbee packet structure has MAC address, device type information, protocol version, flags and sequence numbers. The IAR provides a free kickstart edition with 4K byte size limitation. Optimization techniques can be used to make code size more compact if the size is more than 4K. By attaching the USB stick to the PC with the target board attached, the code can be flashed by option ‘download and debug’ from the project menu. Further information on how to use the IAR Embedded workbench for compiling and debugging was refered from the user guide [12].

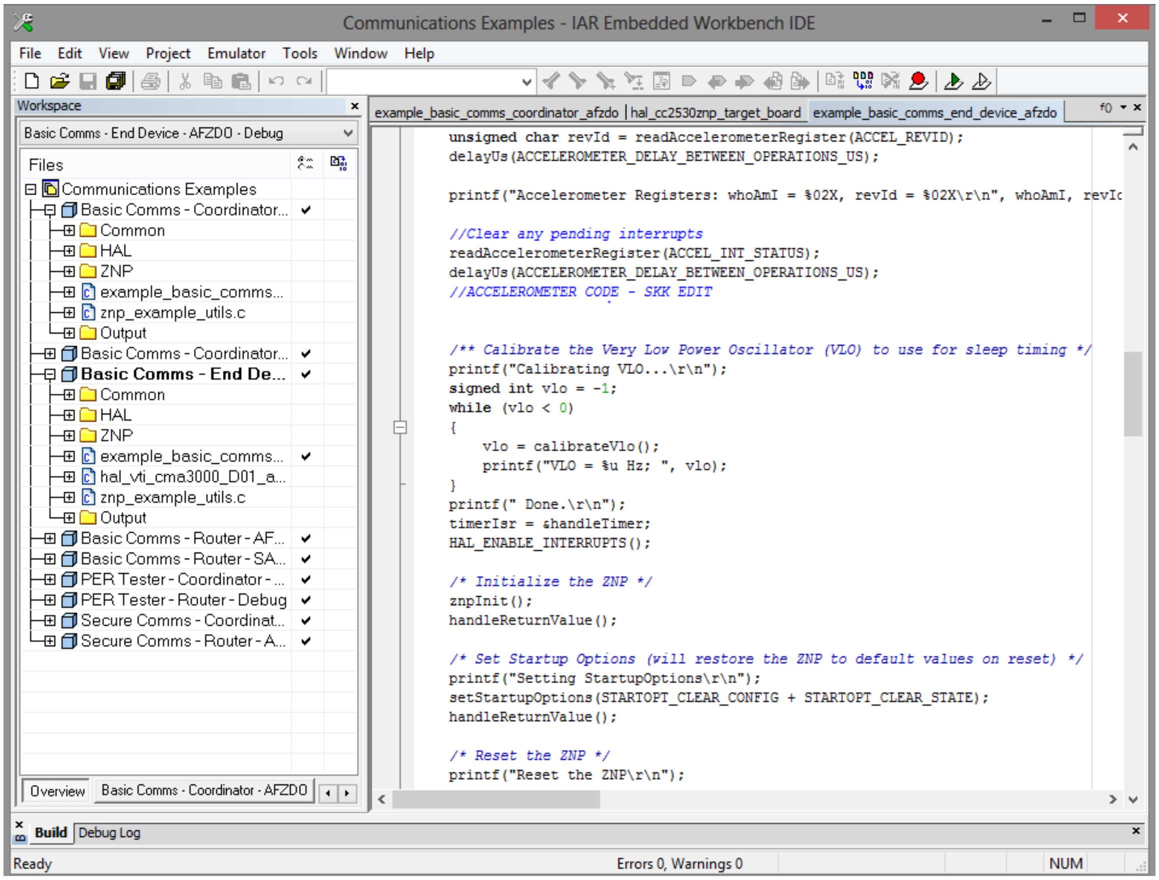

Figure 14: IAR Embedded Workbench IDE

The CC2530ZNP-Mini Kit is the updated version of the EZ430-RF2480. It uses the Zigbee Network Processor (ZNP) firmware on the CC2530 system on chip (SoC). The Zigbee stack can be separated from the applications processor using CC2530ZNP which enables a faster time to market. Hence ZNP gave an easy way to add ZigBee connectivity

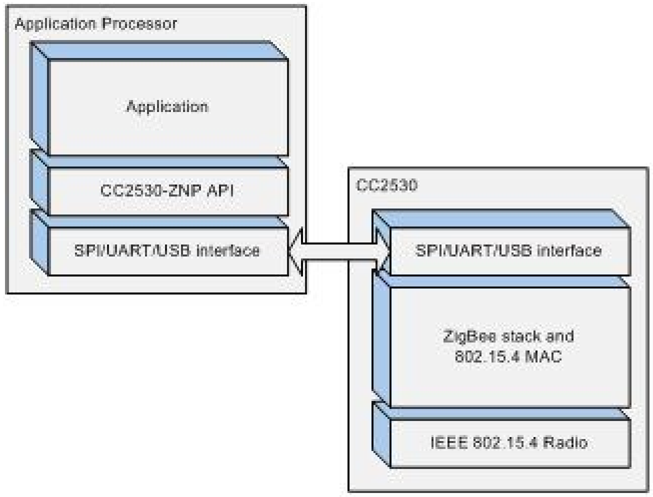

Figure 15: ZNP Application interface

.

to existing systems. All protocol handling of the ZigBee communication is done by a ZigBee processor which allows the existing applications to add a serial interface to a ZigBee processor.

4.7 Humidity Sensor

Figure 16: Humidity sensors

The HIH 5030/5031 is a series of low voltage humidity sensors from Honeywell. These sensors operate at a voltage of 2.7V Vdc. These sensors are suitable for battery operated devices. Also they are suitable for battery operated systems with 3Vdc. The advantage of HIH series sensors from Honeywell is that they can be directly interfaced to a microcontroller. With a typical current of 200μA, the HIH 5030/5031Series is ideally suited for many low drain, battery operated systems. The other features of the humidity sensor as described in [18] are

- Molded thermoset plastic housing
- Near linear voltage output vs. %RH
- Laser trimmed interchangeability

- Low power design
- Enhanced accuracy
- Fast response time Stable
- Low drift performance
- Chemically resistant

The relative humidity from the sensor can be calculated as a function of output voltage and supply voltage.

$$\text{Sensor RH} = (V_{out} - 0.1515) / (V_{supply} * 0.00636) \quad (14)$$

Equation (14). Computes sensor RH at temperature of 25°C

$$\text{True RH} = (\text{Sensor RH}) / (1.0546 - 0.00216 * T), \text{ T in °C} \quad (15)$$

CHAPTER 5

ZIGBEE THERMAL COMFORT SENSOR NETWORK

5.1 Introduction

Home automation is described as improving life style by automating tasks inside homes. Installation of a wired automation system is expensive and messy. A wireless sensor network based home automation system has lot of advantages over wired systems. They are inexpensive, installed and removed any time, cover larger area and can be scaled to incorporate more application areas. Multiple home automation networks can be controlled through the same network infrastructure. Zigbee has had widespread use in home automation. Technological advances have made the possibility for a rapid integrated approach to home automation. This has allowed appliance's to interact with digital technology. Home automation networking has a diverse range of potential applications like lighting, heating and cooling, home security etc. The potential benefits of home automation include

- Easier Lifestyle.
- Security improvement
- Energy savings with cost as well as environment savings
- Flexibility in control and remote control

Smart phone technology has changed life style of people. Integrating home automation with a tablet or smartphone application is not at all a distant dream. Many smart phone manufacturing companies are looking in this area as potential application.

5.2 Zigbee Based Home Automation Systems

One of important applications of Zigbee wireless sensor networks is home automation. Zigbee is used in home automation to build smarter homes that enhance security, comfort, security and energy management. Wide arrays of publications have been published illustrating Zigbee's application in home automation. In reference [8] a flexible designed home automation system based on the Zigbee standard is implemented. This home automation system and WLAN (Wi-Fi) are integrated through a common gateway. The gateway has some simple features like flexible user interface, remote access to system and interoperability of networks. The system effectiveness and feasibility is illustrated by developing a light switch, radiator valve, and safety sensor and Zigbee remote control with home automation system. The author of [9] proposes a Zigbee home automation system based on CC2430 chip. CC2430 provides a System-on-Chip solution for Zigbee application consisting of CC2420 RF transceiver and with an industry standard 8015 Microcontroller unit. In reference [10] smart home design with wireless sensor network based on Zigbee standards was proposed. The system design uses a Texas Instruments MCU device LM3S9B96, which is the ARM Cortex-M3 based controller. The system has a real time embedded operating system with multitasking. Users can access the system based on the TCP/IP protocol stack or GSM SMS. The system gives insight into different parameters of a home such as temperature, humidity, meter readings, and light. Home electronic equipment, such as light, air-conditioning, heating, are controlled by a ZigBee wireless sensor network. Our thesis focuses on measuring thermal comfort with home automation Zigbee networks. Sensed parameters like temperature, humidity, light, and accelerometer and communicated to the coordinator attached to central server. Using the information of temperature and humidity thermal comfort can be computed and analyzed.

5.3 Zigbee Thermal Comfort Model

The designed system with a Zigbee wireless sensor network can be used as a home automation system as described in [3]. Instead of interfacing home appliances we have used a humidity sensor to compute relative humidity in compliance with environmental humidity. These readings are used for computing the PMV index for calculating thermal comfort. The advantage of this system compared to other systems from others system to compute thermal comfort is

- Simple architecture
- Wireless connection between central unit and end-devices
- Easy installation
- Standard Zigbee protocol adaptation system
- System can be extended with multiple end-devices as routers
- Remote control and flexible interface

The TI CC2530ZNP mini kit hardware and software for implementation is discussed in the following section for thermal comfort computation. Experimental results prove that the system is feasible and practically adaptable.

5.4 Hardware Implementation

Designed around the CC2530ZDK-ZNP-MINI kit from Texas Instruments, the hardware unit as well includes the Honeywell humidity sensor HIH 5030/5031.The block diagram shown in Fig. 17 below gives implementation details.

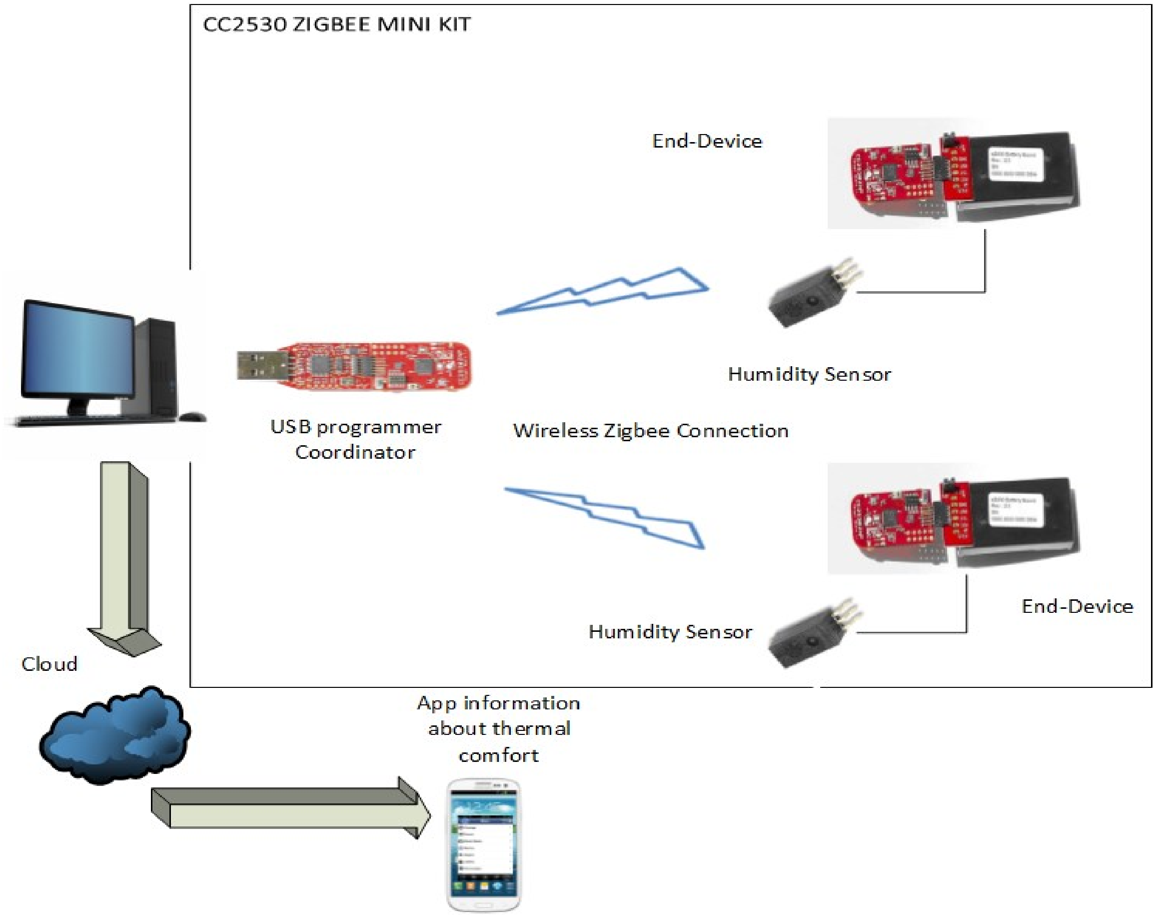

Figure 17 : Flow diagram with humidity sensor attached to Zigbee boards

5.4.1 End device setup

The hardware and software setup details of CC2530ZDK-ZNP-MINI kit are explained in Chapter 4. The hardware of CC2530ZDK-ZNP-MINI kit includes a MSP430F2274 Micro-controller that controls the ZigBee device and a CC2530 ZigBee device preprogrammed with ZigBee software. From Fig 17 we can see that the humidity sensor is attached to the end-device (battery-sensor). Fig 18 shows those I/O access pins. The end-device has 10 dedicated pins and uses 6 pins directly to connect humidity sensors or for matter any external devices as direct input to MSP430F2274. These are I/O pins that can interface to port 2 of the MSP430F2274. The ten pins are described in the following table

Table 3: I/O pins access of end-device

P2 Pin name	Configuration
1	GND
2	VCC
3	MSP430 P2_2
4	MSP430 P4_4
5	MSP430 P2_3
6	MSP430 P4_5
7	MSP430 P2_4
8	MSP430 P4_6
9	MRDY/ MSP430 P3_6
10	SRDY/MSP430 P2_6

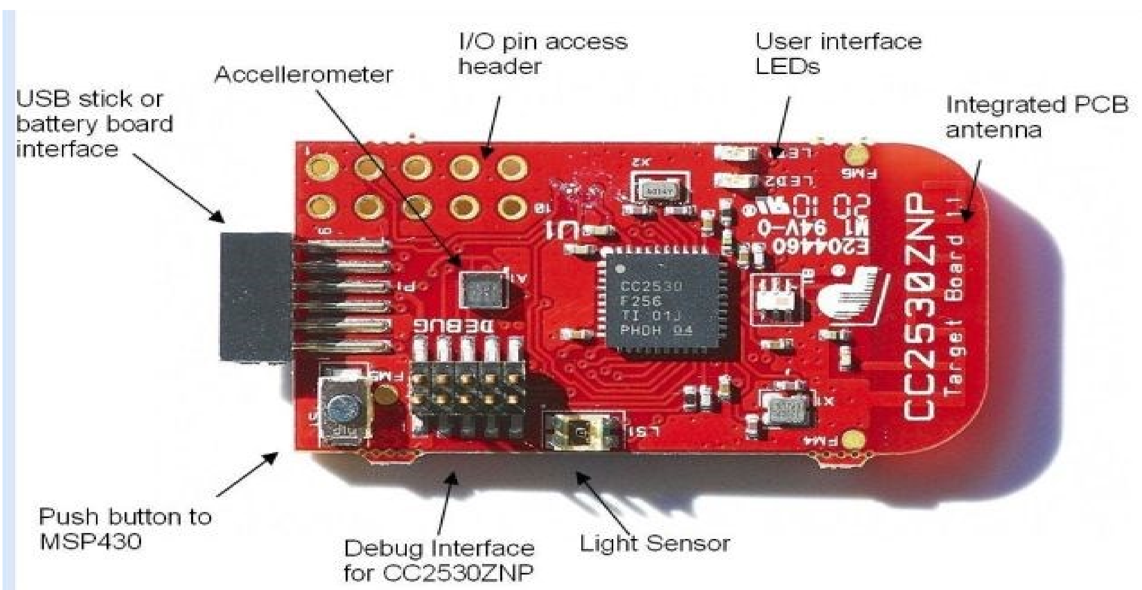

Figure 18: Diagram showing I/O pins access header

The humidity sensor has 3 different terminals. The vcc pin takes a voltage of 3V, a ground terminal and other is analog input voltage.

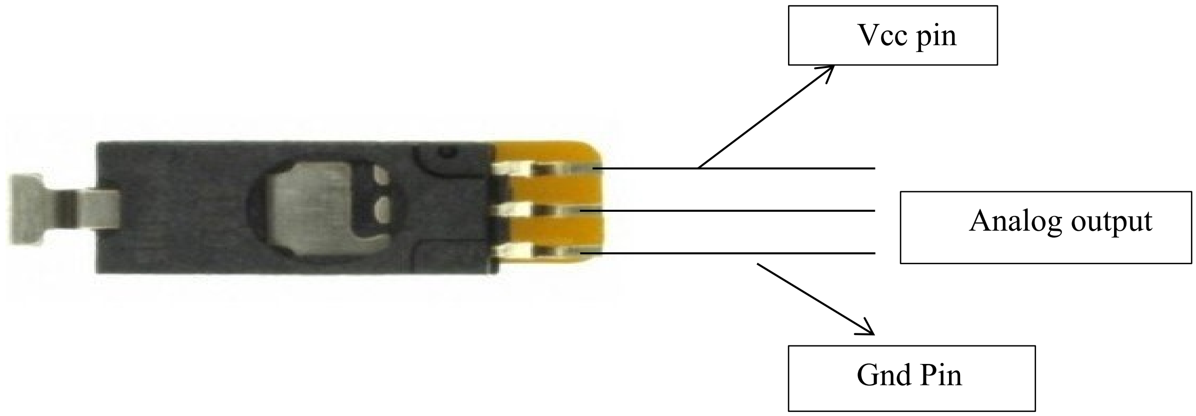

Figure 19: Pin description of humidity sensor

The analog output pin is connected to the p2.4 of the battery sensor board. The vcc pin is connected to the P2.2 of same board and the gnd pin is connected to Pin 2.1 of the battery sensor board. The port P2.4 is an analog input (A4), which means the analog input at this port is routed to an in-built 12 bit ADC which converts the analog input into digital form.

The MSP430F2274 has an inbuilt temperature sensor. The microcontroller was programmed to measure temperature in Fahrenheit. The CC2530 kit also has dedicated accelerometer and light sensor. All the sensors combined together measure temperature, humidity, light and accelerometer readings periodically and send data to the coordinator in packet format. The packet format is shown in Fig 25. Typically the hardware for coordinator, end-device and router are similar and any end-device can be programmed as router.

5.4.2 Coordinator set up

The target board connected to the USB stick programmer acts a coordinator. The coordinator program is flashed to the board so it will be running coordinator application.

This USB programmer can be used for 2 purposes, one as a debugger or programmer and as a virtual serial interface. This means that the coordinator is required to be connected during normal operation. The coordinator is responsible for normal operation, configuring network and starting of network. A Zigbee network has only one coordinator. On opening the serial terminal accessed by the path Windows/Start menu/Accessories/Communication/HyperTerminal the initial configuration of the zigbee network can be seen in the form of messages. Inserting battery to the end device activates the end-device and starts capturing sensor data from the device and this display on the HyperTerminal.

15.5 Software Implementation

5.5.1 Coordinator

The generic sequence of coordinator programming as described [3] is as follows.

1. Initialize the hardware

2. Reset the ZNP

3. Set Startup Options (STARTOPT CLEAR CONFIG + STARTOPT CLEAR STATE)

- upon reset this will restore the ZNP to a blank configuration

4. Set the Zigbee Device Type as COORDINATOR, ROURTER, or END DEVICE

5. Turn on callbacks

6. Register the application

7. Start the application

8. LED indication that the device has started successfully.

The coordinator program flowchart referenced from [3] is in Fig 20 and 21.

Figure 20: Flow Chart of Coordinator Node

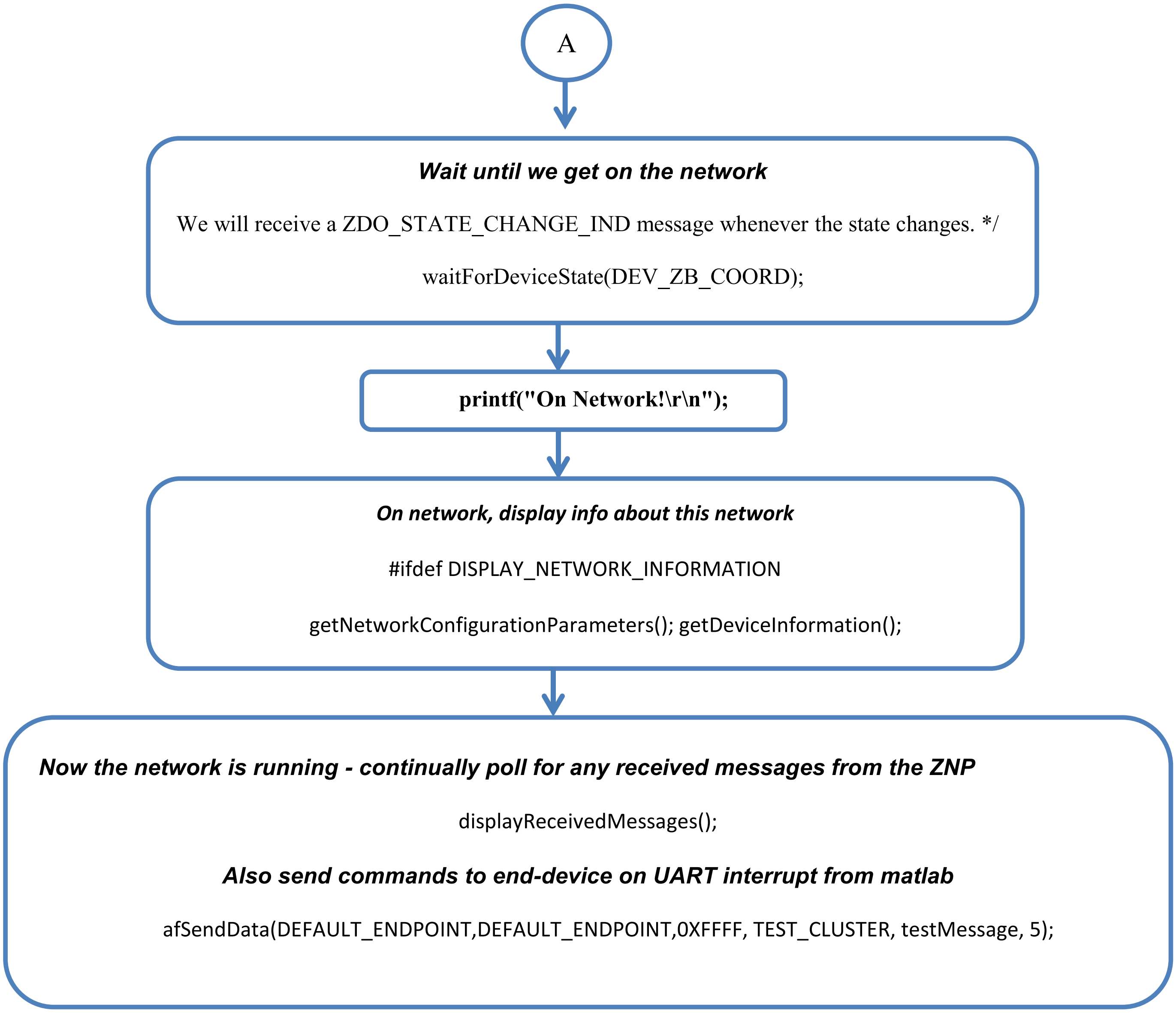

Figure 21: Flow chart of coordinator Node (continued)

5.5.2 End-device

The Zigbee end-device is configured periodically to send sensor data on start up with a sleep in between transmissions. Accelerometer changes its readings up-on motion interrupt. A shared SPI port is initialized every time when we wish to use between accelerometer and ZNP. A separate function to calculate temperature and humidity is written in the program to compute the sensor readings from these sensors respectively. Analog to digital converters are enabled and disabled every time when these functions are called. The detailed flow chart referenced from [3] for the end-device is shown below.

End-Device - using AFZDO

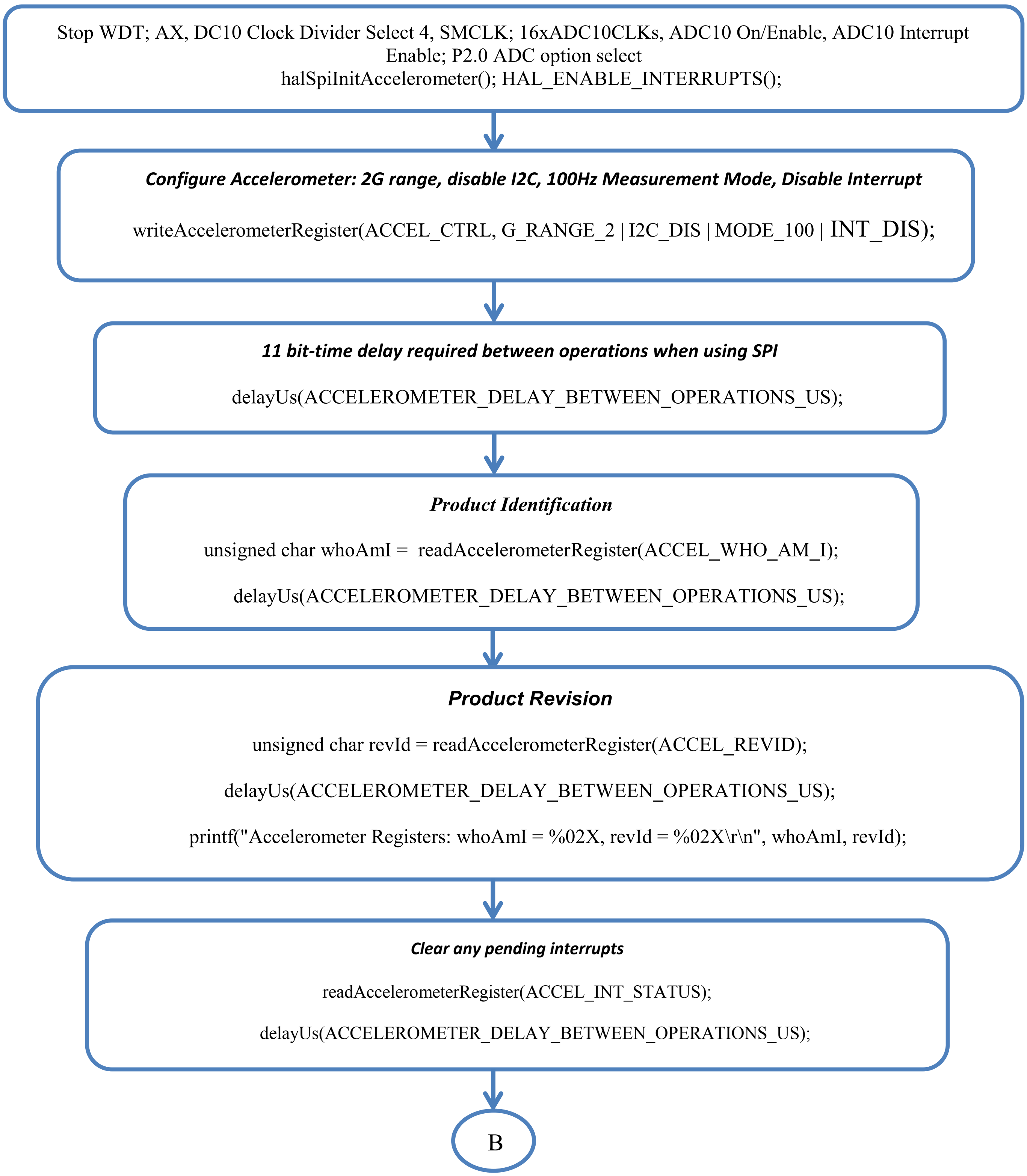

Figure 22: Flow Chart of End Device Node

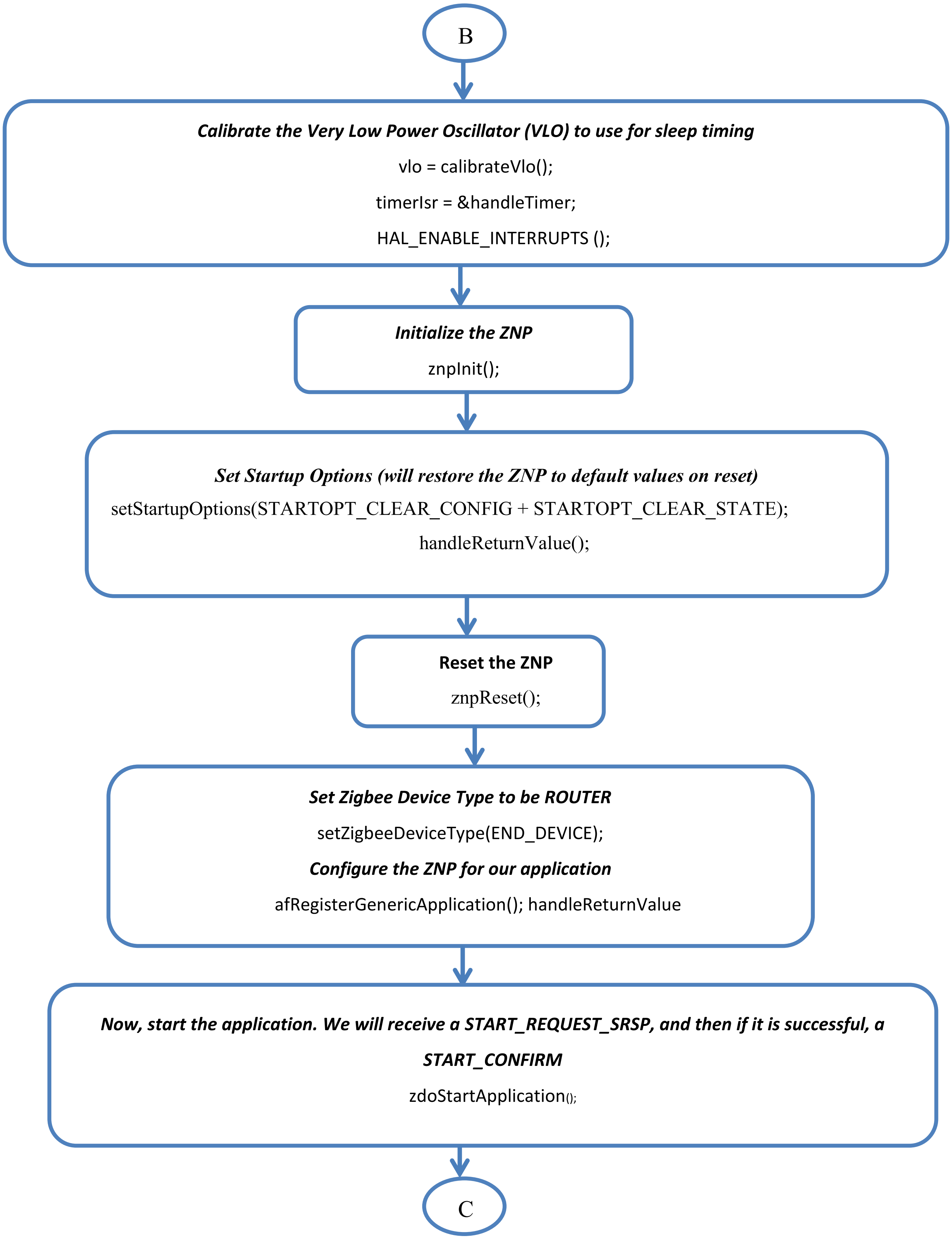

Figure 23: Flow chart of End Device Node (continued)

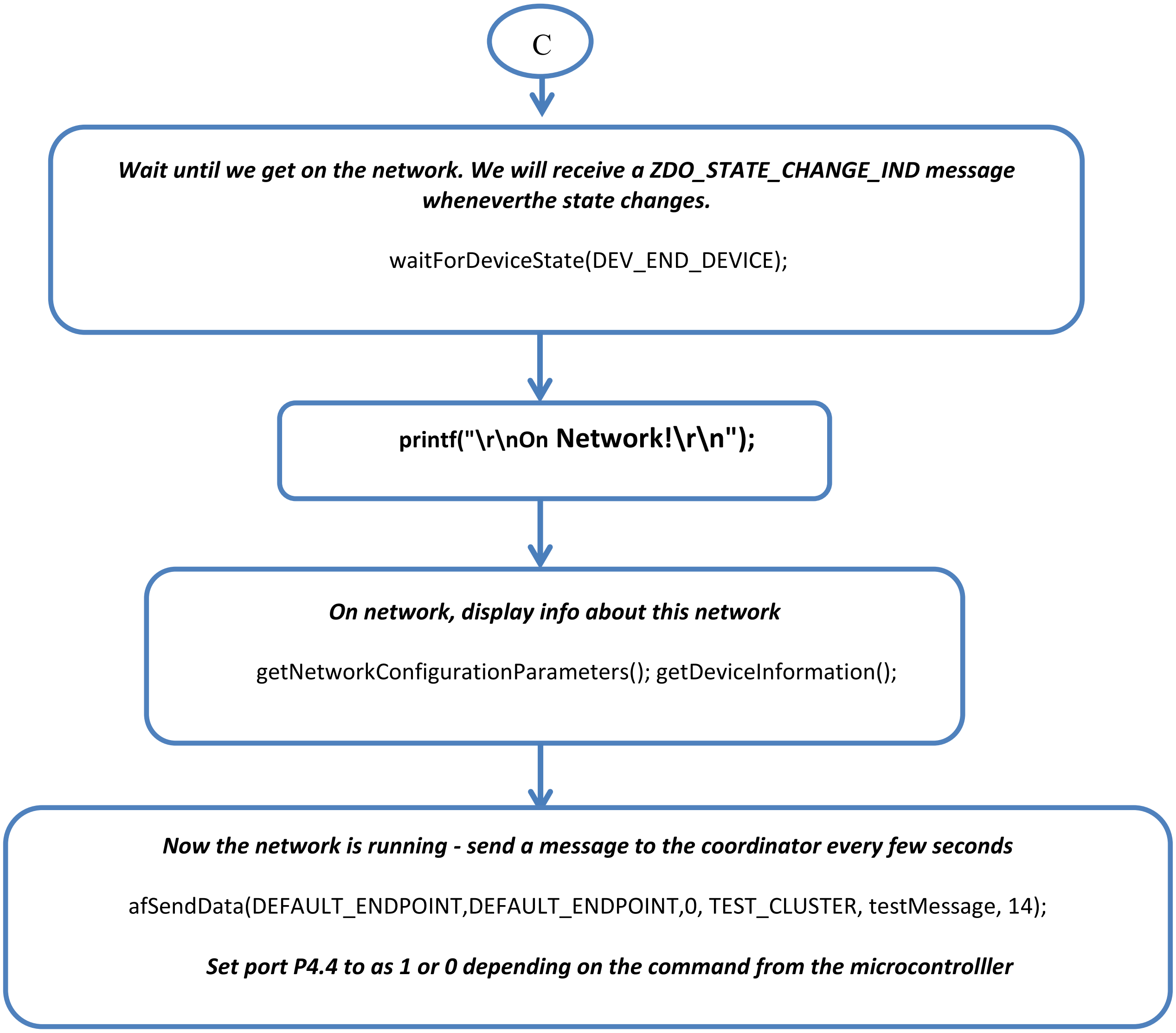

Figure 24: Flow chart of End Device Node (continued)

The format of the packets sent from end-device to coordinator is as shown in Fig. 25. Each packet has a message header, which includes sender's MAC Address, device-type information, protocol version, flags and sequence numbers.

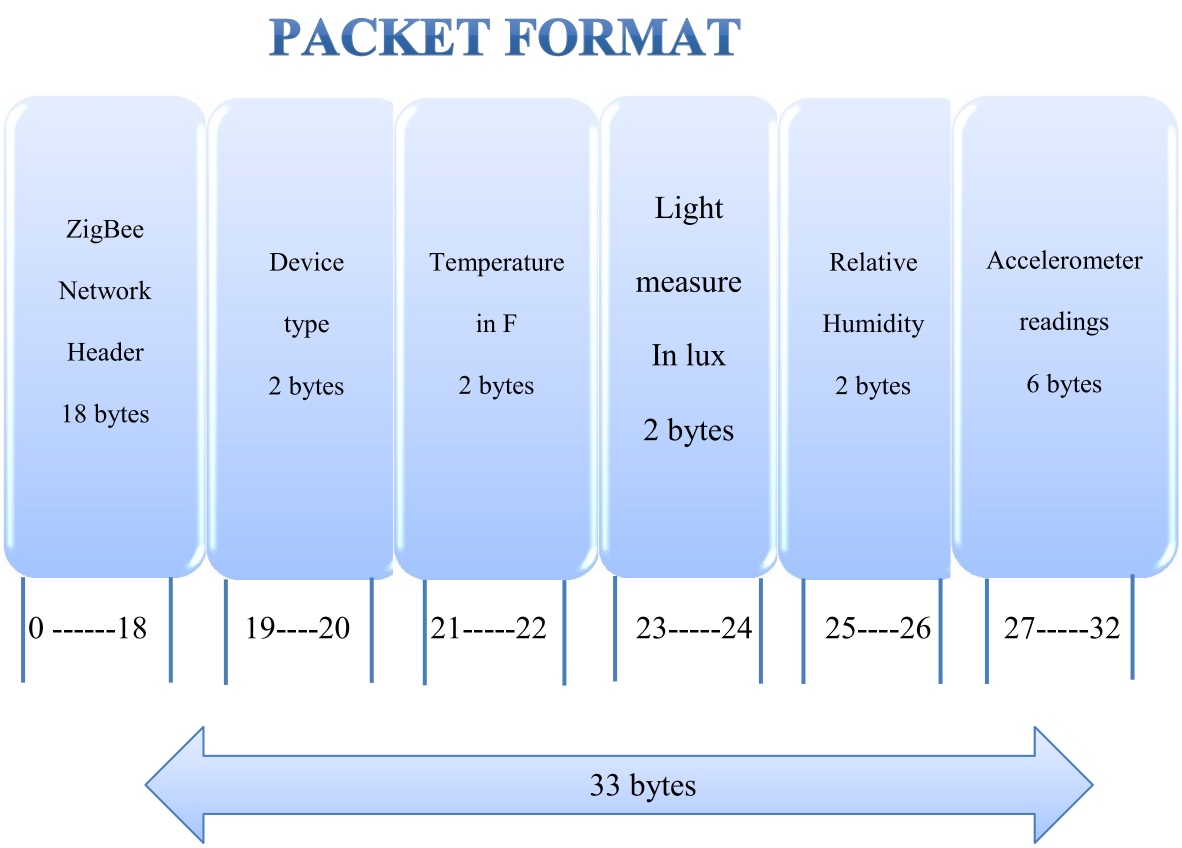

Figure 25: Packet Format

Using the equation (15) and conversion factor shown below

$$Dec2Hex(Nadc)= 1023*(Vin/Vsupply)$$

we can obtain the value of %RH.

CHAPTER 6

SIMULATION AND RESULTS

6.1 Experimental Setup

The Fig. 17 shows experimental set up of the Zigbee thermal comfort sensor network. The humidity sensor connected to the end-device in shown below in Fig. 26. Humidity was computed and along with other information like temperature, light and accelerometer readings, put in packet format as in Fig. 25, and transmitted to the coordinator. A set of live captured humidity and other readings are shown in Fig. 27. The humidity readings are highlighted in the blue column as in Fig 27.

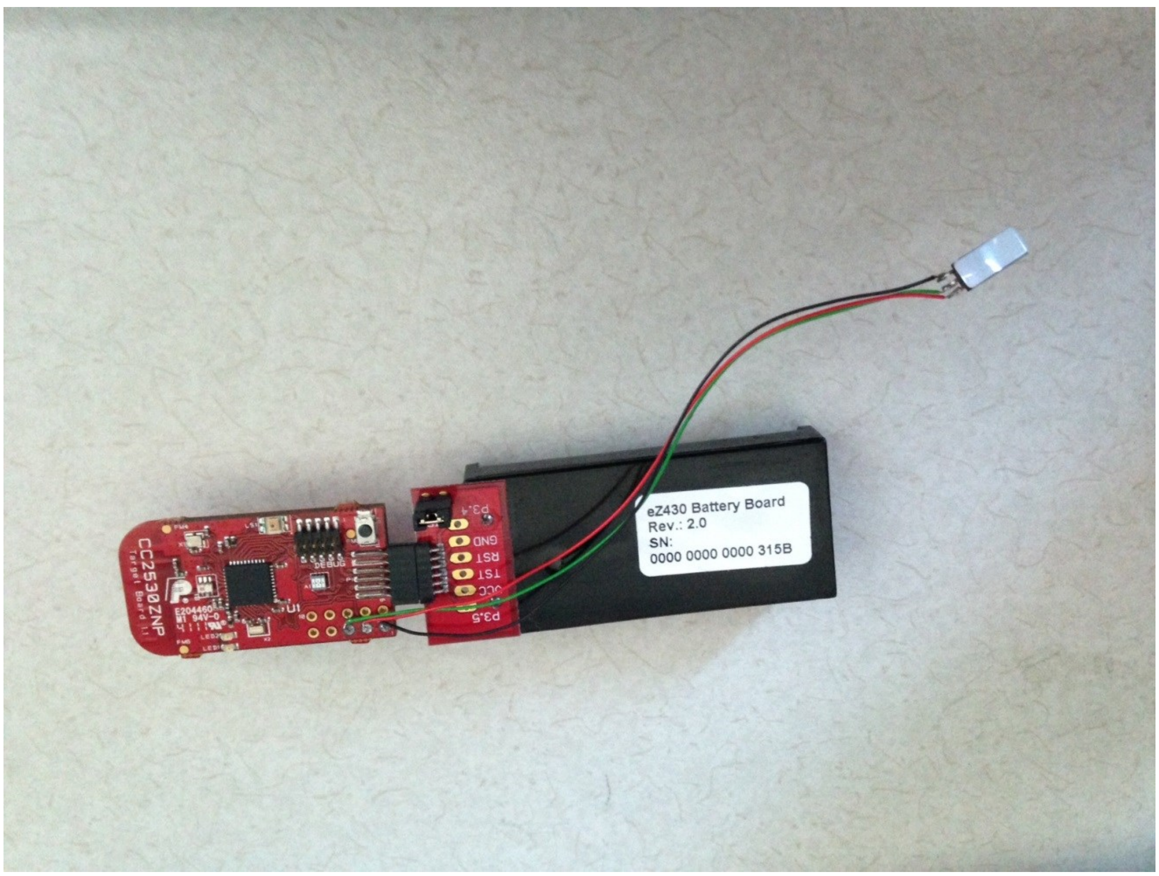

Figure 26: Honeywell Humidity sensor attached to Zigbee End-device

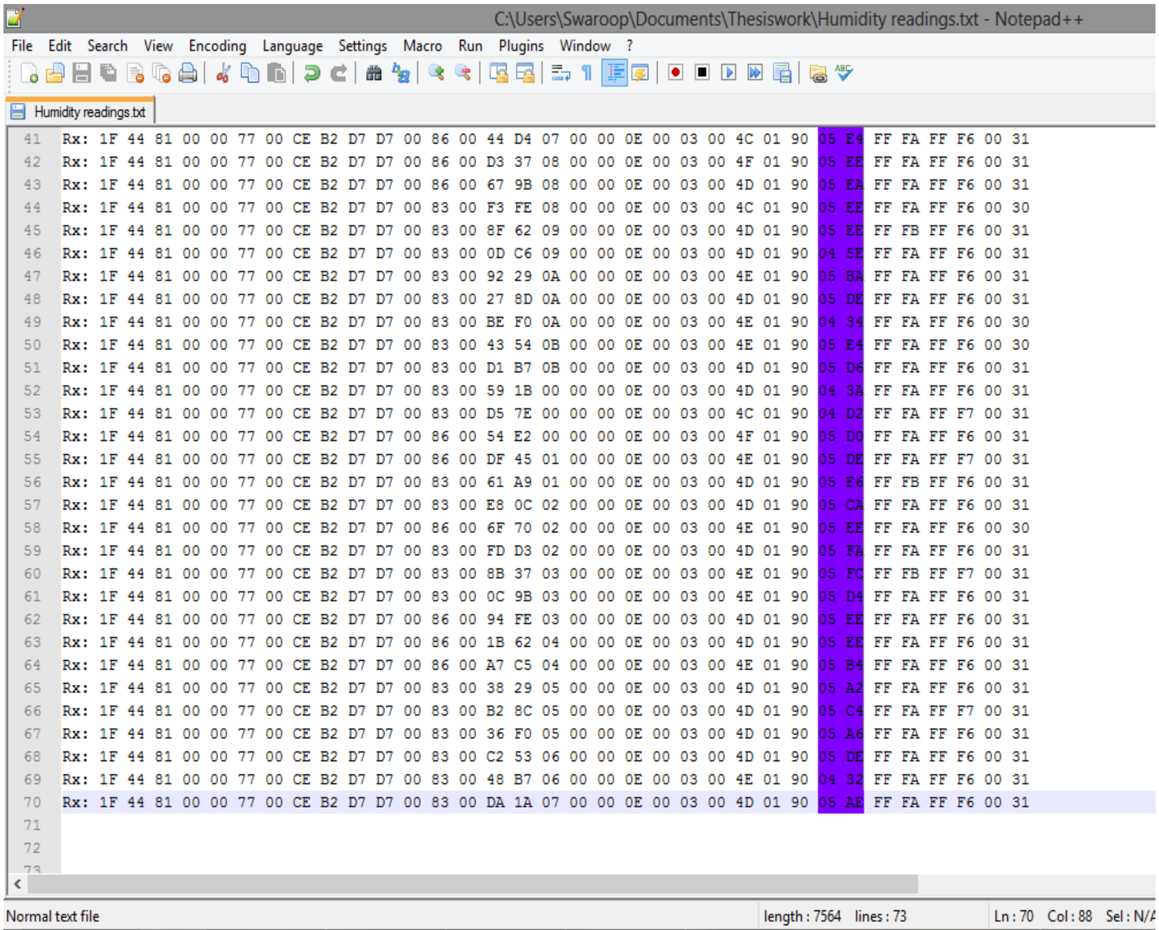

Figure 27: Humidity Sensor readings captured in a text file

6.2 Humidity Computation

The Zigbee wireless sensor networks were interfaced with a humidity sensor from Honeywell. The humidity was computed with the formula shown in (14) at 25°C. The humidity at temperature T was computed with formula (15). The Fig 28 below is a plot of variation of output voltage versus relative humidity at different temperatures.

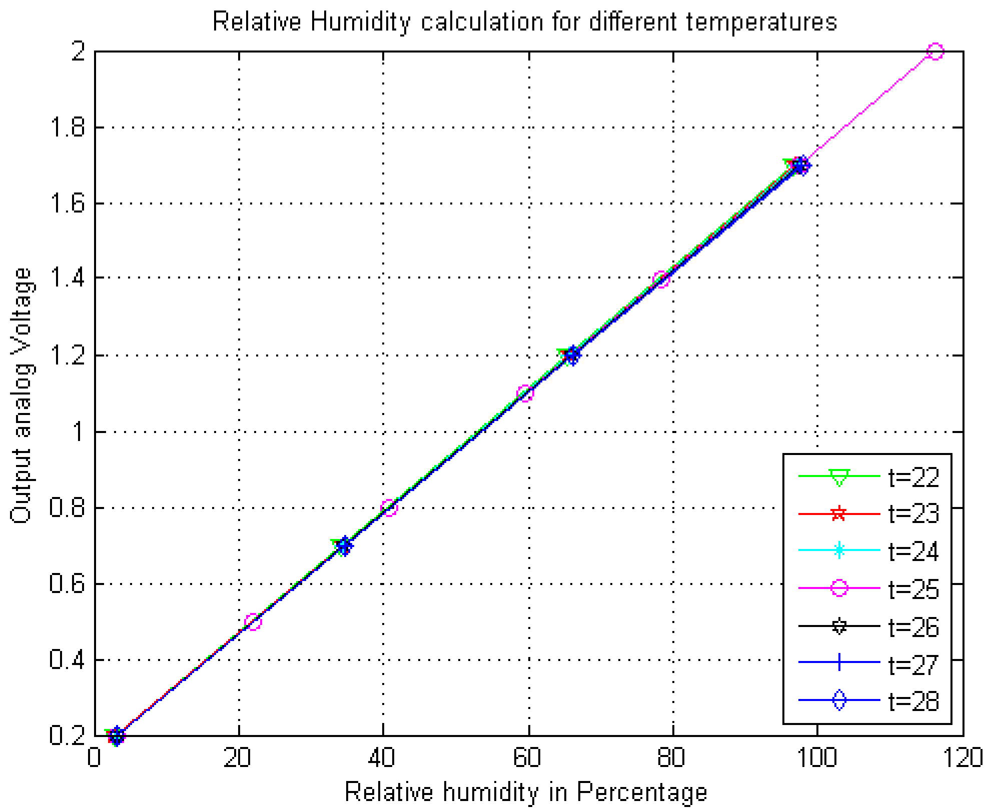

Figure 28: Relative Humidity calculation at different temperatures.

The below graph in Figure.30 shows a computed humidity at Vdc of 3.3V and temperature of 25°C. Based on (14), humidity values were computed with Zigbee CC2530ZNP boards. The average value of temperature was computed by averaging 100 values of temperature received from the temperature sensor. The average value was about 25.19°C. At this temperature, theoretical and practical values were computed and compared as shown in the graph of Fig. 30. From the graph we infer that at a temperature of about 1V relative humidity was about 25% theoretically and 40% practically which is quite agreeable .The practically plotted values agree with practical values measured with a digital multi-meter because the output voltage of the sensor corresponds to obtained relative humidity at that temperature and input voltage. Even though there is small percentage variation in relative humidity the analog output voltage and output voltage after ADC conversion were same with very little variation of 0.001mV.

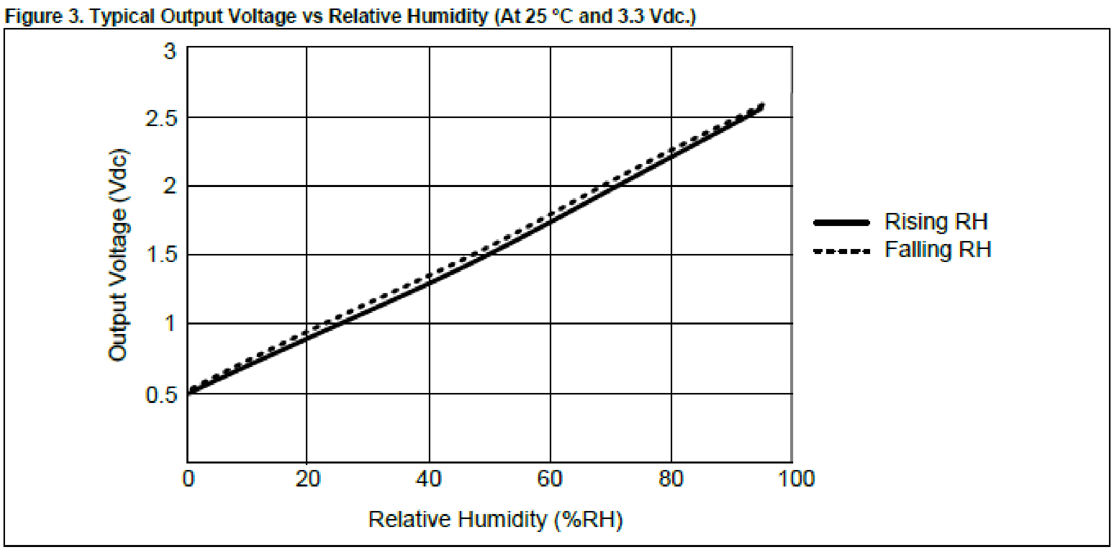

Figure 29: Humidity values from data sheet [18]

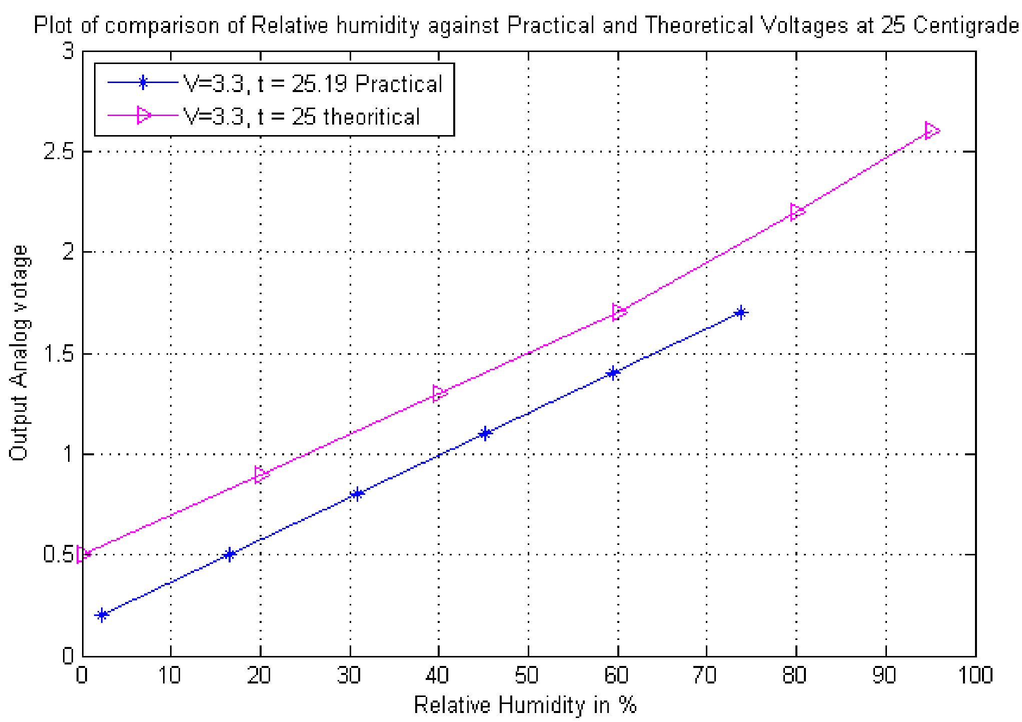

Figure 30: Practical and theoretical comparison of Relative humidity

6.3 PMV Computation

MATLAB simulations were used to plot variation of PMV against air temperature and Relative humidity. In plotting these graphs some assumptions were made as discussed below and these assumptions seem to be reasonable under certain conditions. Our PMV computation is mainly with in indoor environments. Different curves are given based on metabolism levels. We assumed that air temperature is equivalent to radiant temperature and air velocity indoor environments varied from 0.1 m/s to 0.3 m/s. As we see in PMV formula from equations (10), (11) and (12), a lot of factors are interdependent and some factors are to be calculated recursively. One such factor is clothing temperature. We assumed an initial value of clothing temperature to be 25°C and the final value of clothing temperature was calculated in a loop iteratively.

6.2.1 PMV Variation with Air Temperature

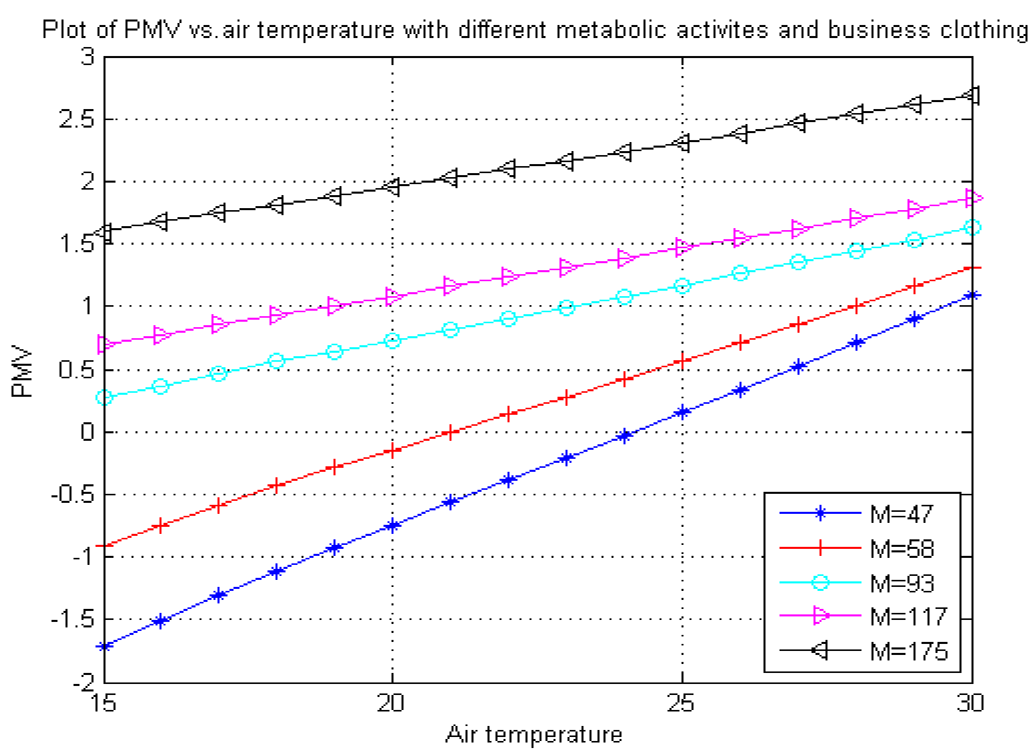

Figure 31: PMV vs. air temperature with Business clothing

The metabolic activity is calculated from table 1. From the plot of Fig. 31 we observe that an increase in temperature tends to increase PMV. This is quite reasonable because we know as temperature increases is a perfect sign of a hot environment. Also from the graph in Fig 31 we see that lower metabolic activity has a low PMV as compared to higher metabolic activities. This means that muscular activities generate heat inside the body and may lead to an increase in body temperature which in turn increases PMV.

6.2.2 PMV Variation with Relative Humidity

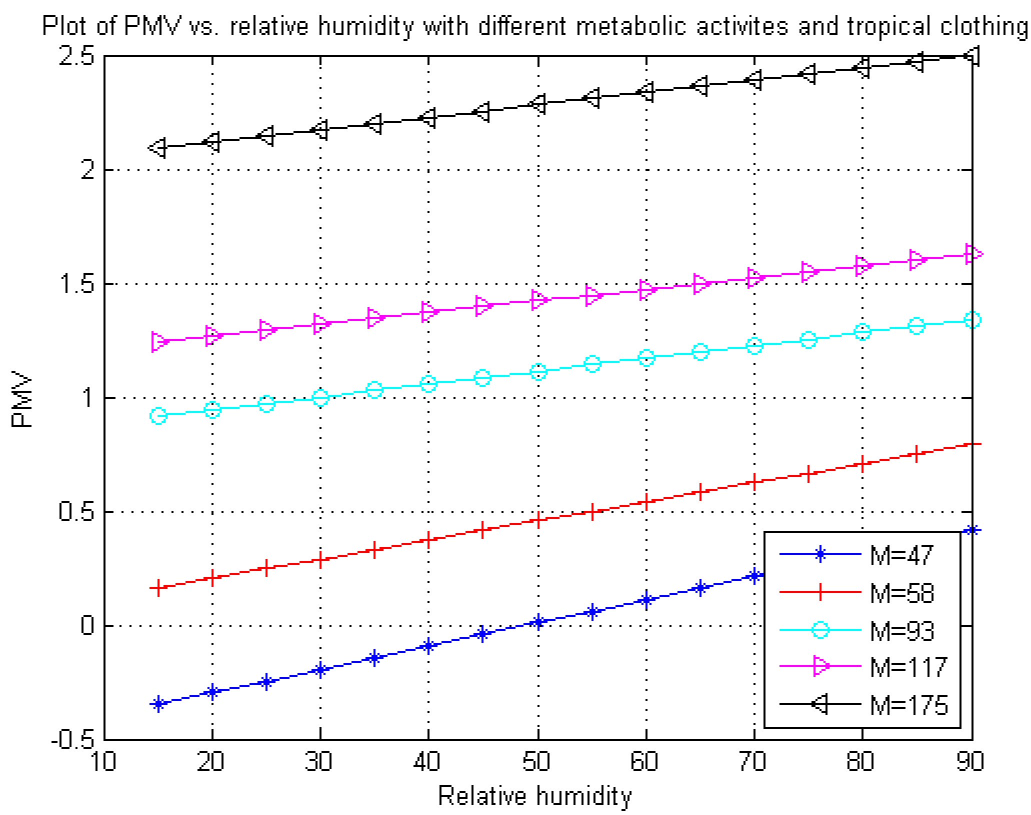

Figure 32: PMV Plot vs. Relative humidity with tropical clothing

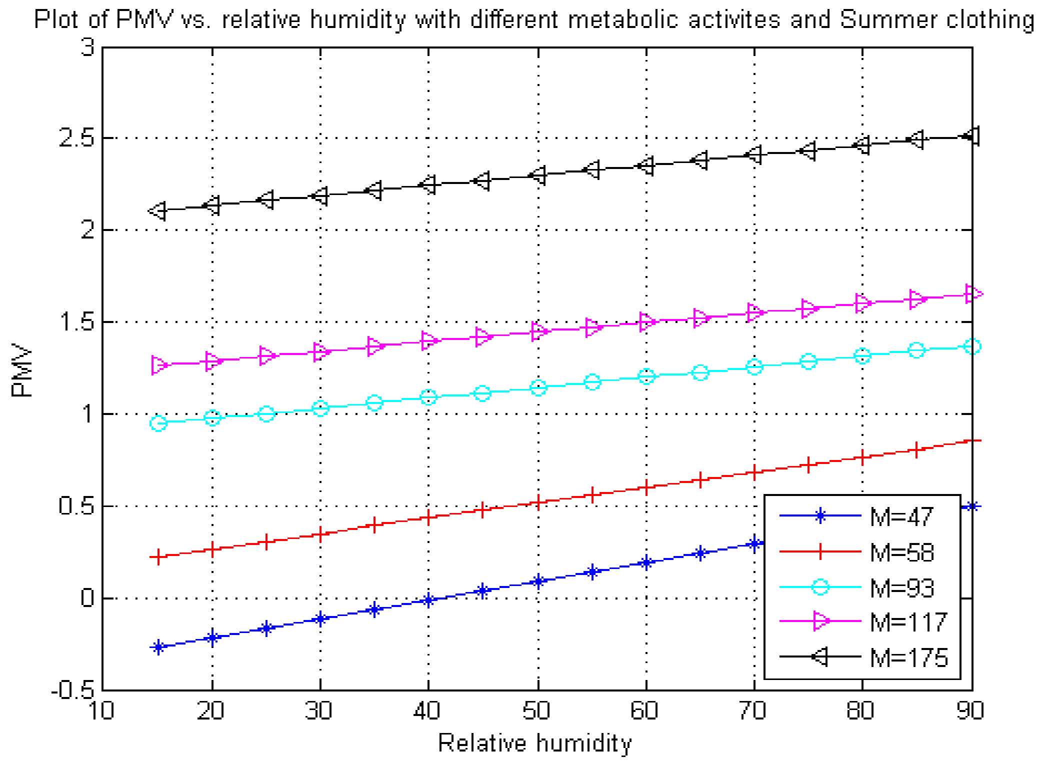

Figure 33: PMV Plot vs. Relative humidity with summer clothing

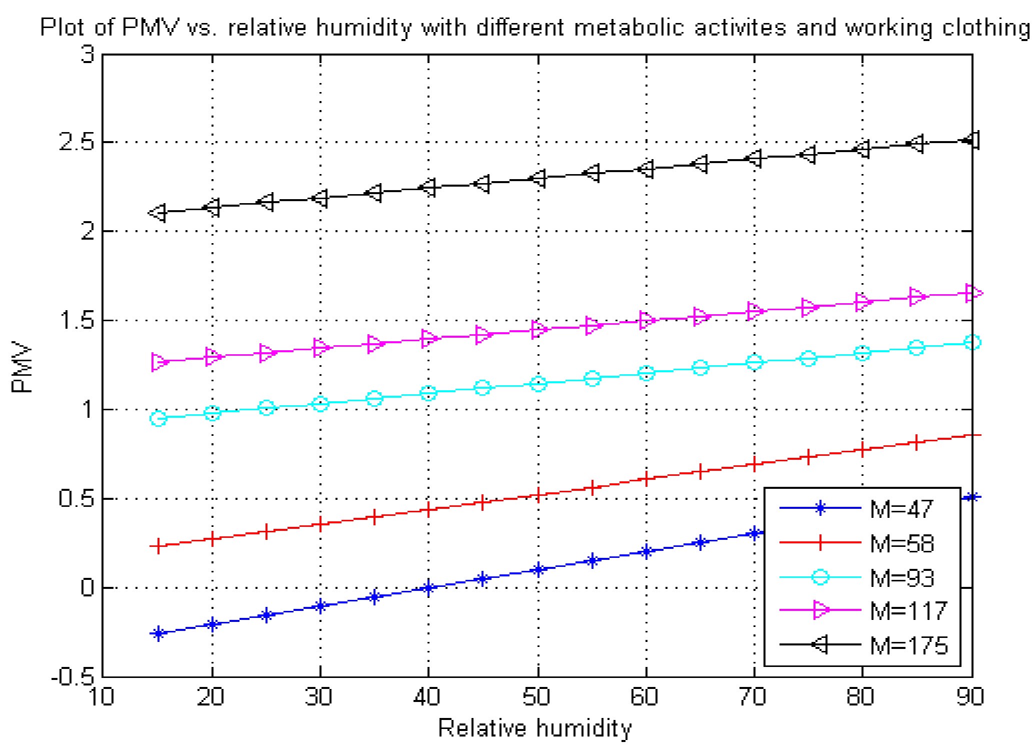

Figure 34: PMV Plot vs. Relative humidity with working clothing

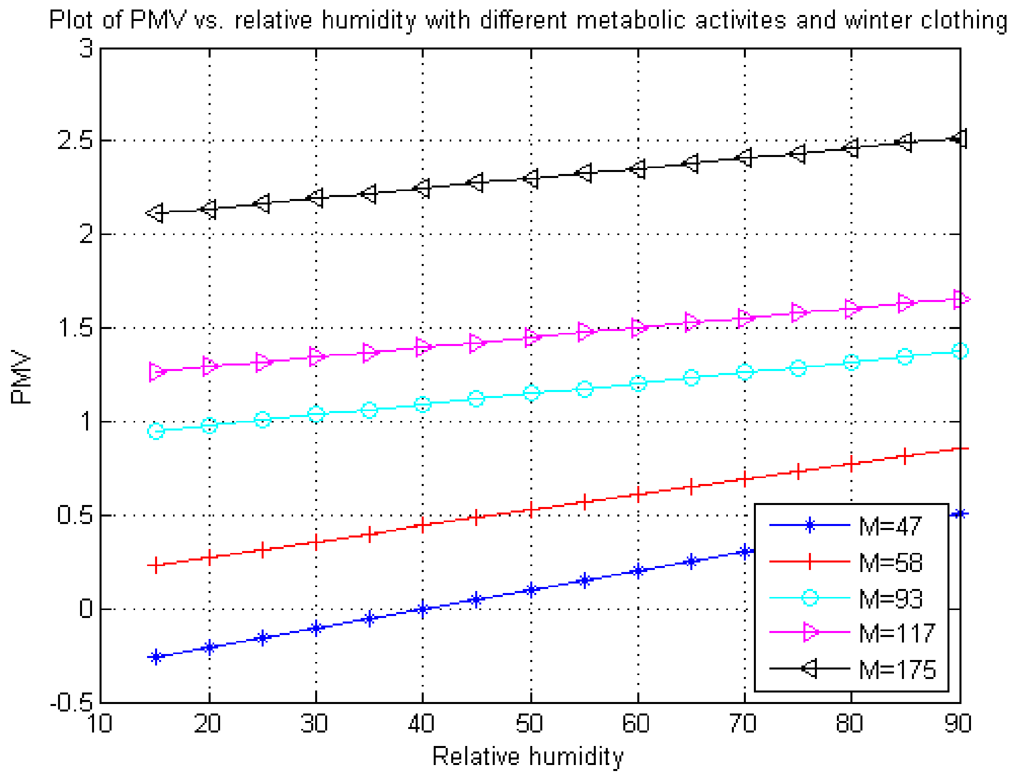

Figure 35: PMV Plot vs. Relative humidity with winter clothing

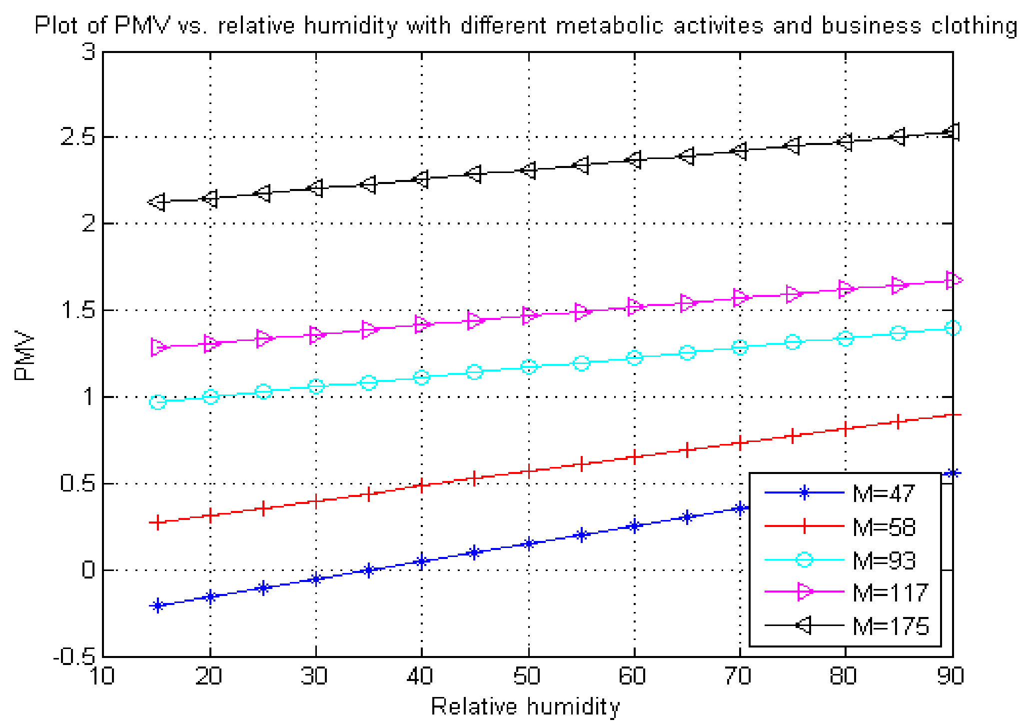

Figure 36: PMV Plot vs. Relative humidity with Business clothing

The variation of PMV w.r.t to Relative humidity was plotted with Fig.32 to Fig.36. From these graphs we observe that lower humidity indicates plots towards cooler scale of comforts and higher humidity towards hotter scale of comfort. A medium activity with business clothing has the best PMV compared to others. So for any clothing PMV factor between 0.5 to -0.5 and 40% to 50% seems to be a proper value.

6.2.3 PMV Variation with Different Clothing

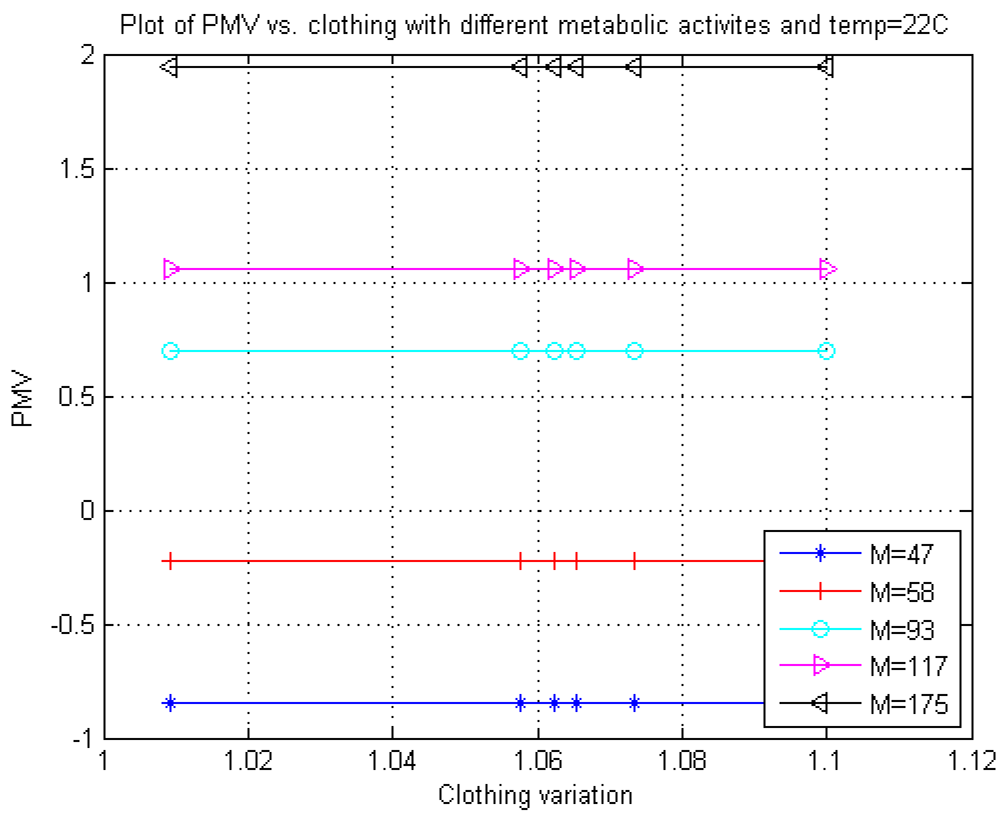

Figure 37: PMV plot vs. clothing at temperature 22°C

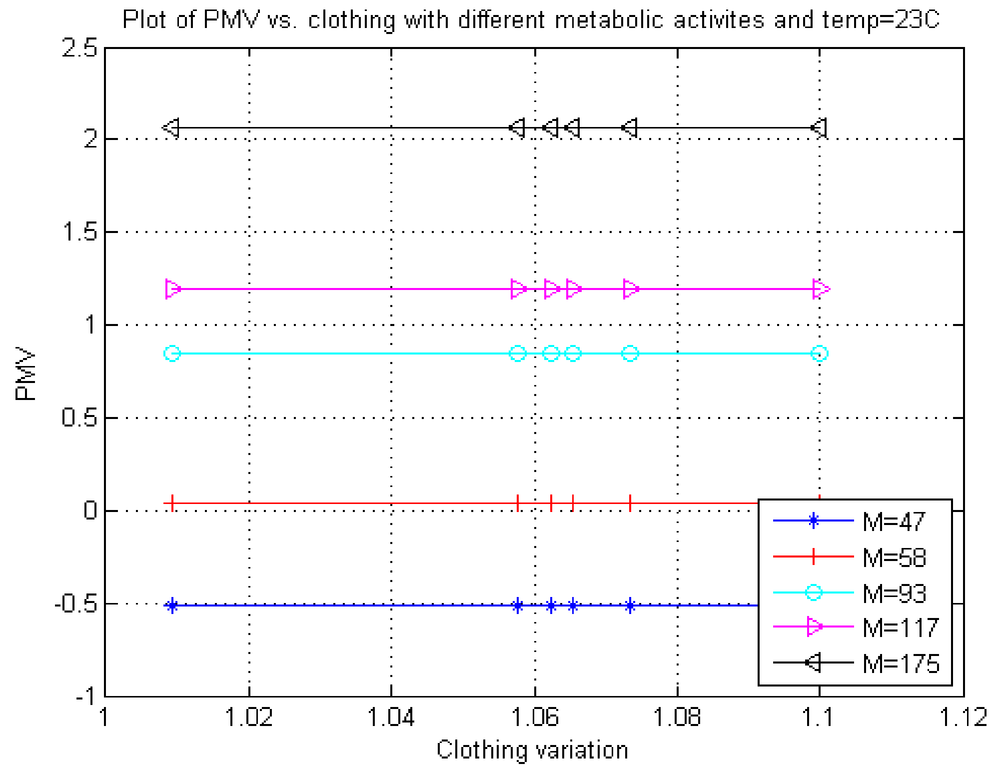

Figure 38: PMV plot vs. clothing at temperature 23°C

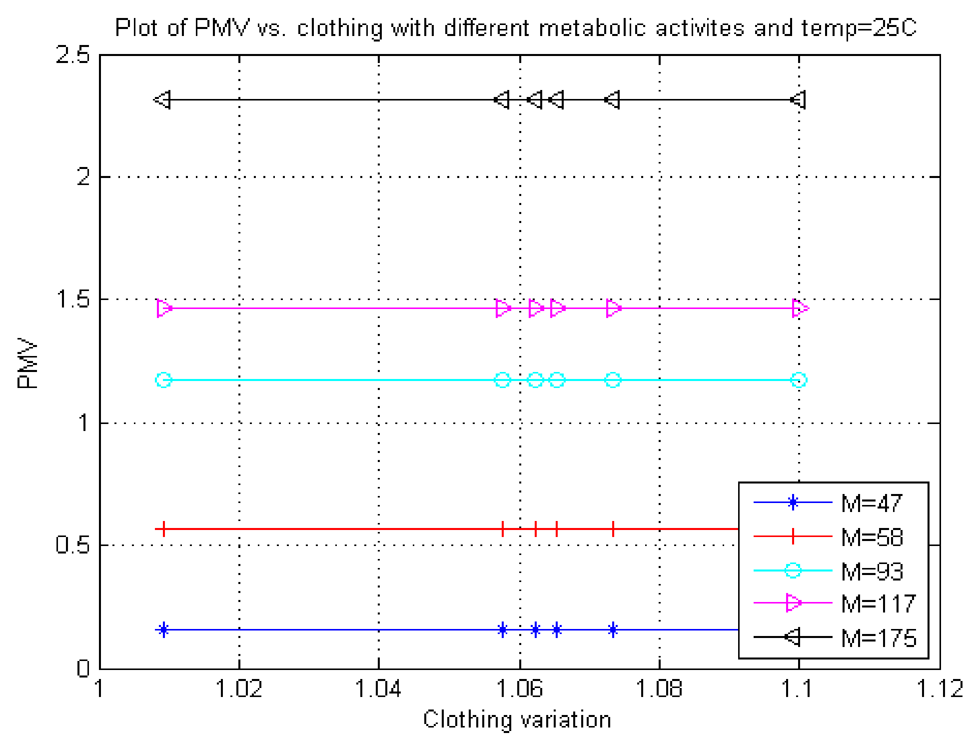

Figure 39: PMV plot vs. clothing at temperature 25°C

The plots from Fig 37 to 39 describe variation of PMV against different clothing at different room temperatures. The plots also show variation against different metabolism. We assumed that radiant temperature and air temperature are equal. Higher metabolic activity always indicates higher PMV and lower metabolic activity hops towards region of appropriate comfort levels. So change is clothes do not have much impact on PMV until there is change in metabolic activity

6.2.4 PMV Variation with Different Air Velocities

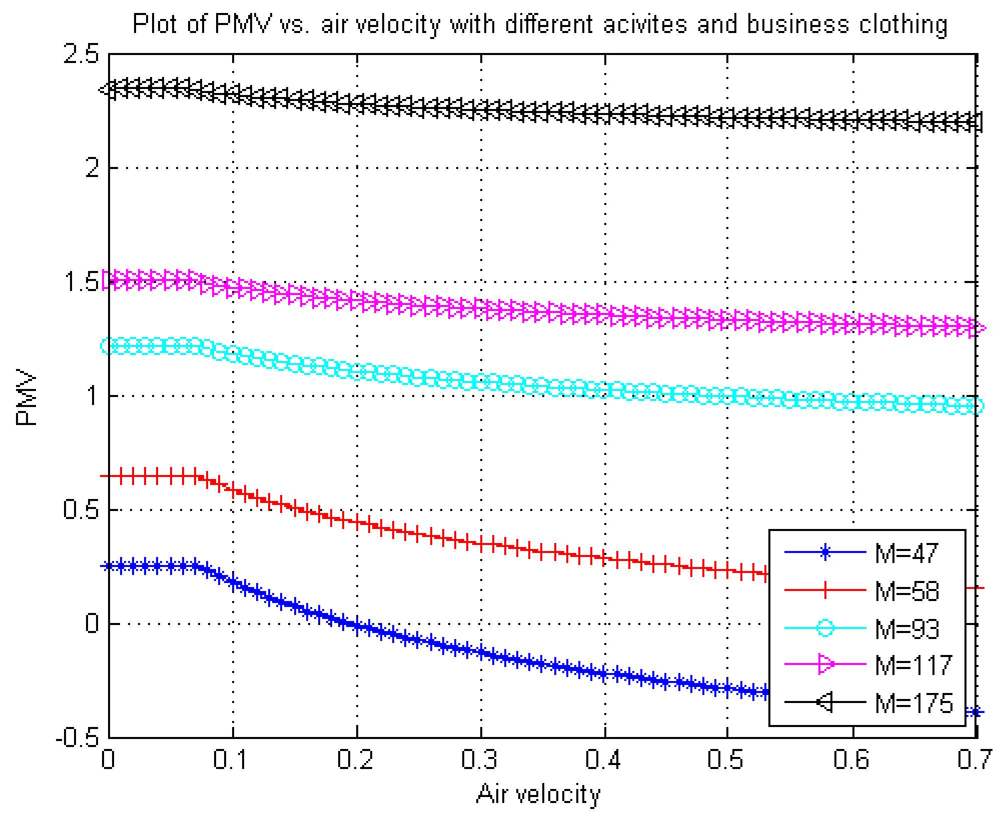

Figure 40: PMV plot vs. air velocity

Figure 41: PMV vs. air velocity for clothing temperature less than air temperature

The two plots in Fig 40 and Fig 41 show variation of PMV with respect to air velocity. Air temperature and radiant temperature are equal and all other parameters are kept constant. From Fig 40 we see that if clothing temperature is less than air temperature the PMV levels tend to cool comforts for increasing air velocity. The other graph in Fig 41 shows that PMV levels tend to a region of hot comfort levels for increasing air velocity. It's a kind of reasonable argument because clothing influences the flow heat to and from the body. Until the clothes that people are wearing comes to equilibrium levels with air temperature or room temperature there will changes or different feeling with respect to comfort levels.

CHAPTER 7

THERMAL COMFORT AND COST

7.1 Introduction

Energy consumption and cost are two critical parameters that have to be considered when operating AC, heater or any other part of the HVAC (Heat, Ventilation and Air Conditioning) system. The cost of operating any home appliance depends on energy consumption. It also depends on the amount of time the appliance is operated and also usage of the appliance. For example heaters are not operated in summers and air conditioners are not operated in winters. There operating costs will be null during summers (heaters) and winters (air conditioners) respectively.

HVAC system design has significant influence on the energy consumption. HVAC system based on thermodynamics, fluid mechanics and heat transfer principles have some ingenious designs within the system to save energy and reduce cost.

7.2 Energy vs. Cost

In this thesis and a part of research work of E-save project, we calculate cost for energy consumption of appliances used in providing thermal comfort. Air conditions, fans, heaters and thermostat are some of the devices used in providing thermal comfort in indoor environments and in compliance with temperature of surroundings. The basic idea is to use alternative resources that will provide similar thermal comfort experience, compare their energy consumption and cost if they are operated. The three factors used to calculate energy consumption of any electrical appliance are

1. Home Appliance usage in hours
2. Power in watts consumed by home appliance
3. Cost of 1 kilowatt-hour(1kWh=1000Wh) of electricity

Multiplying the first two factors and dividing by 1000 gives total energy consumption in kWh. Knowing cost of 1 kWh we can calculate the total cost for operating home appliances for so many hours.

Table 4: Energy consumption of different appliances [15] [22]

Appliance	Wattage in watts	
Air Conditioner	900 for 5000 BTUH room unit	1500 for 12000 BTUH room unit
Ceiling Fan	100	
Electrical Furnace Heater	20000	
Portable room heater	1500	
Electric Space Heater	1400	

The average energy consumption is calculated from the [16]. Different states have different cost per kWh of energy consumed. So table 5 gives an average cost in different regions.

Table 5: Average energy consumption cost in different regions of USA

Different regions of USA	Average energy consumption Per kWh in cents
East	12.73
Central	12.28
West	10.05

If fans run all day without being turned off and AC runs 50 % of the time, energy consumption per month are as follows

Energy consumption for Fan per day = 100*24/1000=2.4kWh

Energy consumption per month = 2.4*30=72kWh.

Energy consumption for AC per month = 0.5*1500*24*30/1000=540 kWh

Consider a scenario with a hot summer, temperature around 30°C,

1. Increase AC to 60% utilization
2. Operate Fan for only 15 hrs. when home

Energy consumption for AC per month = 0.6*1500*24*30/1000= 648 kWh

Energy consumption for Fan per month = 100*15*30/1000=45kWh

Table 6: Cost calculation for First scenario in summer

Appliance		East		Central		West	
	Running time (hrs.)	**24**	**15**	**24**	**15**	**24**	**15**
		Total cost per month in dollars					
Fan		**9.16**	**5.72**	**8.84**	**5.52**	**7.23**	**4.52**
	AC utilization	**50**	**60**	**50**	**60**	**50**	**60**
		Total cost per month in dollars					
AC(12000 BTUH)		**68.74**	**82.49**	**66.31**	**79.57**	**54.27**	**65.12**

The cost of operating a Fan came down by 60% since the number of hours was reduced by 9hrs per day but AC cost increased approximately by 20% for increasing AC utilization by 10% in different regions of the USA.

Consider a scenario with low temperature around 15°C in summer,

1. Decrease AC to 20% utilization
2. Operate Fan for about 7 hrs. at home

Energy consumption for AC per month = 0.2*1500*24*30/1000= 216 kWh

Energy consumption for Fan per month = 100*7*30/1000=21kWh

Table 7: Cost calculation for second scenario in summer

Appliance		East		Central		West	
	Running time (hrs.)	**24**	**7**	**24**	**7**	**24**	**7**
		Total cost per month in dollars					
Fan		**9.16**	**2.67**	**8.84**	**2.57**	**7.23**	**2.11**
	AC utilization	**50**	**20**	**50**	**20**	**50**	**20**
		Total cost per month in dollars					
AC(12000 BTUH)		**68.74**	**27.5**	**66.31**	**26.52**	**54.27**	**21.70**

The cost of operating a Fan came down by 70% since number of hours was reduced by 17 hrs. but AC cost reduced approximately by 60% for decreasing AC utilization by 30% in different regions of USA. In summary, balancing the operation of fan and AC helps in reducing the cost depending on the temperature of surroundings and indoor environments.

The discussion till now was related to summer conditions with calculation of energy cost in different scenarios. We considered scenarios like hot temperature and cold temperature in summer. The next scenarios are similar to above discussed cases except with winter conditions. In winter in most of the homes in USA, people use heaters to keep themselves warm. Different kinds of heating systems like central heating, space heating, radiant heater and convection heaters are used in homes. The most commonly used is the central heating which heats every nook and cranny of the house. This system may result in use of a lot of energy when regions of home are heated which are totally unnecessary. If one or two rooms of a home are to be heated space heating suits the best and will be consuming less energy than central heating. Radiant heaters are used to heat part of a room.

In calculating the cost we are making some assumptions. They are

1. The average size of home in US is assumed to be 3000 square foot
2. An electric furnace with 20kW is used to heat home

If an electrical furnace runs all day with 80% utilization in winter and a space heater runs for 6hrs. , energy consumption per month is

Energy consumption for electrical furnace = 0.8*24*20000/1000=384kWh

Energy consumption per month=384*30=11520kWh

Energy consumption for space heater per month=1400*6*30/1000=252kWh

Consider a scenario with cold temperature being around 5°C

1. Decrease Electric Furnace utilization to 50%
2. Use space heater for 12hrs.

In this scenario energy consumption will completely change. Under these conditions

Energy consumption for electrical furnace = 0.5*24*20000/1000=240kWh

Energy consumption per month=240*30=7200kWh

Energy consumption for space heater per month =1400*12*30/1000=504kWh

Table 8: Cost calculation for different scenarios in winter

Appliance		East		Central		West	
	Running time (hrs.)	**6**	**12**	**6**	**12**	**6**	**12**
		Total cost per month in dollars					
Space Heater		**32.07**	**64.15**	**30.94**	**61.89**	**25.32**	**50.65**
	EH utilization	**80**	**50**	**80**	**50**	**80**	**50**
		Total cost per month in dollars					
Electric Furnace Heater		**1466.4**	**916.56**	**1414.65**	**884.16**	**1157.7**	**723.6**

To summarize, the operation of different heating devices providing thermal comfort in winter, the cost of operating space heater increased by 50% but cost of operating heater came down by 37%. The total cost operating for 6 winter months comes down.

7.3 Thermal Comfort Opinion

We discussed in section 2.1.1 and 2.1.2 the factors affecting the thermal comfort. Accordingly these factors are influenced by cost. We can control metabolic activity, relative humidity, air temperature, air velocity and clothing temperature in indoor home environment. Here in this thesis we try to give guide lines based on the PMV levels plotted in the graphs in section 6.3 of the chapter 6.

Scenario 1: Let us consider the graph in Fig. 31 where temperature versus PMV is plotted. If the temperature is at 25°C, base PMV for M=117 is 1.1. A level of comfort could be achieved if PMV should vary between -0.5 and +0.5. If we reduce relative humidity from 50% to 30% PMV comes to a level of 1.3 from Fig. 32. The reduction in humidity may be by using heater inside the home which adds to cost. We observe from Fig. 40 using a fan may not improve comfort level either since increase in air velocity (using a fan at higher speeds) makes PMV level constant. So the best way to change comfort level is to change metabolic activity which may be make us very comfortable. So the advice is don't waste money by changing AC or the heater. If we change metabolic activity from M=117 to M=58 a PMV level of 0.5 will make us definitely better.

Scenario2: Let us consider the graph in Fig. 31 where temperature versus PMV is plotted. If the temperature is at 15°C, base PMV is -1.7. The comfort level can be achieved from -0.5 to +0.5 level according to thermal comfort scale. An increase in temperature to 24°C will take comfort level to 0 as per the Fig 31. The increase in temperature is costly. A humidity level increase from 40% to 50% will achieve a required comfort level. We have to weigh our options and check if required comfort level is achieved at expense of cost. It's obvious that we want to achieve required comfort level at lower cost and see if temperature increase or humidity increase will increase the cost. The advice is that on availability of different options we have to see if comfort can be achieved at lower cost.

The main aim of this thesis is to compute PMV, a thermal comfort index, and give opinion about thermal comfort in home indoor environments. A series of MATLAB simulations and plots in section 6.3 of Chapter 6 indicated variation of PMV with respect to environmental factors as well as personal factors. When variation of PMV was plotted w.r.t to relative humidity the plots from Fig 32 to Fig 36 clearly indicate that to maintain thermal comfort levels an optimum relative humidity of 45% to 50% is said to be comfortable. Lower relative humidity indicates cooler comfort levels and higher humidity indicates warmer comfort levels which is an indication of appropriate result. The other plots for variation of PMV w.r.t to air temperature and air velocity are reasonable enough show that PMV formula is ok to yield good results under certain assumptions. Even though lots of factors are assumed to be constant their behavior is totally unpredictable.

This may sometimes mislead to plots of PMV against personal or environmental factors. PMV is one of the tool to compute thermal comfort and there are advantages and disadvantages of this tool like any other tool.

CHAPTER 8

CONCLUSION AND FUTURE WORK

In this thesis and thermal comfort research, we explored the possibility of thermal comfort calculation by an index called PMV using Zigbee wireless sensor networks. The end-devices used in our work had rechargeable batteries. We know that wireless sensor networks can be driven by supercapacitor and a lot of research is being done in this area. Supercapacitors are huge capacitors with capacitances in Farads. In literature there are innumerable examples explaining of using supercapacitors to drive wireless sensor networks. Energy harvesting sources are used to drive these capacitors. Energy harvesting source like solar energy, thermal energy, wind energy etc. are used to charge capacitors and store energy. Stored capacitor charges are used to drive various system on chip boards. One possibility is exploring ways of driving these networks with energy harvesting sources and capacitors. Our idea is to measure home thermal comfort by attaching these sensor networks at home. A possibility is that we attach a 3V adapter to the end-device, then end-devices are plugged to the walls of the house at different end places and by the readings we can calculate thermal comfort. So a combination of energy harvesting sources driving our Zigbee Wireless Sensor Network and attaching them to walls at home at low cost may form a feasible solution in computing thermal comfort.

REFERENCE LIST

[1] Jinsoo Han; Haeryong Lee; Kwang-Roh Park, "Remote-controllable and energy-saving room architecture based on ZigBee communication*," Consumer Electronics, IEEE Transactions on*, vol.55, no.1, pp.264, 268, February 2009

[2] Jinsoo Han; Chang-Sic Choi; Ilwoo Lee, "More efficient home energy management system based on ZigBee communication and infrared remote controls," *Consumer Electronics (ICCE), 2011 IEEE International Conference on* , vol.57, no., pp.631,632, 9-12 Jan. 2011

[3] Sarika Kumar "Design of a wireless platform for wearable and home automation applications" Master's Thesis, University Of Missouri Kansas-City (2012)

[4] Neng-Sheng Pai; Yao-Hong Ou; "A Comfort System Base on ZigBee Wireless Monitoring and Control in Smart Home" *Fifth Smart Living Technologies Symposium,* 15 September 2010

[5] Dasheng Lee; "Development of Light Powered Sensor Networks for Thermal Comfort Measurement" *Proceedings of Sensors 2008*, vol. 8, pp. 6417-6432;

[6] Nall, D. H. (2004-11). Looking across the water: Climate-adaptive buildings in the United States & Europe. *The Construction Specifier*, 57, 50 – 56.

[7] A book on ANSI/ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy.

[8] Gill, K.; Shuang-Hua Yang; Fang Yao; Xin Lu, "A Zigbee-based home automation system," *Consumer Electronics, IEEE Transactions on* , vol.55, no.2, pp.422,430, May 2009.

[9] Yang Li; Ji Maorong; Gao Zhenru; Zhang Weiping; Guo Tao, "Design of Home Automation System Based on ZigBee Wireless Sensor Network," *Information Science*

and Engineering (ICISE), 2009 1st International Conference on. pp.2610, 2613, 26-28 Dec. 2009.

[10] Chunlong Zhang; Min Zhang; Yongsheng Su; Weilian Wang, "Smart home design based on ZigBee wireless sensor network," *Communications and Networking in China (CHINACOM), 2012 7th International ICST Conference on* , pp.463,466, 8-10 Aug. 2012.

[11] CC2530 reference from http://www.ti.com/cc2530znp

[12] CC2530 example programs from http://processors.wiki.ti.com/index.php /Simple_Applications_Examples

[13] 2009 ASHRAE Handbook Fundamentals, ASHRAE, Inc., Atlanta, GA.

[14] ISO 7726. Ergonomics of the thermal environment - Instrument for measuring physical quantities. Geneva, Switzerland: International Organization for Standardization. 11-1998.

[15] Appliance operating costs reference from http://www.glendalewaterandpower.com/rates/appliance_operating_costs.aspa

［16］ Electricity costs in each states reference from http://www.npr.org/blogs/money/2011/10/27/141766341/the-price-of-electricity-in-your-state

[17] www.zigbee.org

[18]Honey well humidity sensor reference from http://sensing.honeywell.com/index.php?ci_id=49692

[19]Elefteria Psillakis, Evangelia Yiantzi, Nicolas Kalogerakis, "Downsizing vacuum-assisted headspace solid phase microextraction*", Journal of Chromatography A*, Volume 1300, 26 July 2013, Pages 119-126, ISSN 0021-9673,

[20] http://ww2010.atmos.uiuc.edu/%28Gh%29/guides/mtr/cld/dvlp/rh.rxml

[21] engquan Yuan; Haiping Xu; Huachun Han; Yingjie Zhao, "Research of smart charging management system for Electric Vehicles based on wireless communication networks,"*Information and Automation for Sustainability (ICIAfS), 2012 IEEE 6th International Conference on* , vol., no., pp.242,247, 27-29 Sept. 2012.

[22] http://michaelbluejay.com/electricity/howmuch.html

VITA

Krishnaswaroop A Jois was born on May 19th 1987 in Bangalore, Karnataka, India. He began pursuing undergraduate studies in Bachelor of Engineering at Dayananada Sagar College of Engineering affiliated to Visvesvaraya Technological University, Bangalore, India in Electronics and Communication Engineering and finished in 2009 with First class distinction honours.

After his under graduation he was working as a Project Assistant at Indian Institute Of Science, Center for Electronics Design and Technology (formerly CEDT), currently , Department of Electronics Systems Engineering for two years under guidance of T.V. Prabhakar.

Mr. Krishnaswaroop A Jois joined Master's program here at University Of Missouri Kansas City in spring 2012. He was awarded CSEE instructional Support award and worked as Teaching Assistant for Electronic Circuit courses under Prof. Jerome Knopp for two semesters. He was also a Research Assistant under Prof. Cory Beard and Dr. Vijay Kumar. As a part of Masters Curriculum he got opportunities to do summer internships in well noted companies Leapfrog Enterprises Inc. and Synaptics Inc. as Firmware Engineering Intern. He has given full time interviews with companies like Qualcomm, Texas Instruments and waiting to hear from them.