TRANSMIT POWER CONTROL
WITH HARVESTING-CAPABLE SENSOR NODES

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Master of Technology

By

Vishal Prajapati

under the guidance of

Prof. Purushottam Kulkarni

Department of Computer Science and Engineering,
Indian Institute of Technology, Bombay

Dissertation Approval Certificate

Department of Computer Science and Engineering

Indian Institute of Technology, Bombay

The dissertation entitled **"Transmit Power Control with Harvesting-capable Sensor Nodes"**, submitted by **Vishal Prajapati** (Roll No: **08305030**) is approved for the degree of **Master of Technology** in **Computer Science and Engineering** from **Indian Institute of Technology, Bombay**.

Prof. Purushottam Kulkarni
CSE, IIT Bombay
Supervisor

Prof. XXX
Dept, IIT Bombay
Internal Examiner

Prof. XXX
Dept, IIT Bombay
External Examiner

Prof. XXX
Dept, IIT Bombay
Chairperson

Place: IIT Bombay, Mumbai
Date: 24^{th} **June, 2010**

Abstract

Non rechargeable battery powered sensor nodes can serve for very little life time with their single charged battery life. Prior studies have been done to improve the life time of the node by efficiently utilizing the battery power. *Energy-harvesting*, converting the ambient energy to electrical energy, has emerged as an alternative to extend the life of the sensor nodes by recharging them simultaneously. With the increase of the *effective energy*[1] per day by getting extra energy from the harvesting module, we have opportunities to tune the sensor node parameters. As part of this work, we aim to exploit the availability of periodic energy harvesting opportunities to tune node-level transmit power. Towards this, we identified three main solution components, (i) harvesting-capable hardware prototype, (ii) accurate energy metering and prediction and (iii) formulation of a harvesting-aware transmit power control problem and its solution. We present the design of our hardware prototype and demonstrate its use to collect energy profiles for harvesting. Further, we present a simple model to predict available energy and present an initial result of its applicability. We identify issues that separate harvesting-aware transmit power control from traditional battery-limited nodes.

[1]effective energy is a function of the expected energy from recharge in a subsequent duration, energy consumed by non-optional tasks and the current battery level.

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Chapter 1

Introduction & Motivation

Wireless Sensor Networks (WSNs) are widely used in today's world. Significant WSN deployment in civilian applications is observed as sensors are more powerful, smaller and less expensive. A large number of sensors can be deployed in both friendly and harsh environments without any communication lines to periodically sense and transmit data to the sink or base station. There are applications like Habitat monitoring[18] - environmental monitoring in wild-life habitats like Great Duck Island and James Reserve, to study weather conditions and animal migratory patterns, Volcano monitoring[27] network of seismometers used in a time-synchronized and event-triggered manner to measure volcanic activity, Structural monitoring[14] - BriMon[3], a sensor network to detect incoming trains and measure the forced and free vibrations of a bridge; and Vehicle tracking[5] - sensors placed along or on roads, and on vehicles, detect road, traffic and environmental conditionsinformation which can be used to warn drivers of potentially dangerous conditions or to inform about traffic conditions for better route planning. In many real-time deployments we don't have enough accessibility of the sensors to change the batteries and the life of the node simply depends on the battery capacity and power consumption rate of the sensor. Some studies have proposed very good solutions techniques for effectively utilization of the life of battery power sensor nodes. Some of the improvement includes energy-aware MAC protocols (SMAC [25], BMAC [20], XMAC [2]), power aware storage, energy efficient routing and data dissemination protocols [7, 9, 15], effective duty-cycling strategies [4, 6], power saving adaptive sensing rate [17], multi tiered system architectures [6, 12, 11] and redundant placement of nodes [26, 13] to ensure coverage guarantees.

After all the optimizations, the issue of life of the battery powered sensor nodes still remains open as the sensor nodes goes dead once battery is discharged. The solutions to enlarge the life of the node is done by decreasing the power wasted in the path finding of routing a packet, by decreasing the duty cycle of the node and keep the node more in power saving mode and only be active when there is sensing is needed to be done. Some proposals suggests about changing the MAC protocol such that the by decreasing the overhead of packet, effectively decreasing packet size, we need to send the less number of bytes over the wireless medium - decreasing all the possibilities of energy wast through wireless communication. Inspite of all this optimizations, the bigger the battery more the life the node have, and when the battery dies the node becomes useless. Major deployment of this applications are in the region where you can not get the nodes back and put them back by simply changing the batteries.

These proposals have elongated the life of the node but still there are trade-off of between the accuracy of the data and the life of the node. One of the solution to this problem is we need to gather the energy from the ambient resources and store it the rechargeable batteries and use them for the operations of the application. Currently, some researches are going on for using the ambient sources to constantly supply energy to the sensor node. Some of the deployments such as Hydrowatch[24], Prometheus[10], Heliomote[21], SolarBuiscuit have been initial steps in the same direction.

Now as we have more energy at each node we can optimize usage of effective energy of the node. Now we don't have to worry about the energy limitation at the node because we are constantly getting the energy from the ambient sources. Now the main goal is to use the available energy at the node in efficient manner. As the harvest-able energy will not be same at all the nodes, the consumption of the energy should also be adapted accordingly. There are various factors that are affecting the usage of energy of the node. For example change in duty cycle, change in transmit power, Change in rate of sensing, Change in no of packets sent per time unit etc. and change in any of this parameter s affects other communication parameters. There has been work done for adapting the duty-cycle to maximize the energy utilization[8] of the node, where they have tried to increase the average duty-cycle ratio of entire network. Our work is in same direction but we are trying to address the same issue by adapting the transmit power parameter. we can formally describe our problem definition as follows.

Definition

As part of this study, we are interested in two main aspects, (i) accurate energy metering and prediction, and (ii) developing a solution for adaptive harvesting-aware tuning of transmit power at each node. Specifically, given a wireless sensor network, with energy-harvesting capable nodes, we aim to keep real-time track of the energy availability. This depends on the energy harvested, energy used, battery capacity, battery efficiency etc. Current and past energy levels will be used to predict future energy availability. For this study, we restrict ourselves to solar energy harvesting. Based on the energy availability trend, the second goal is to tune the transmit power at each node and simultaneously ensure energy neutrality. *Energy neutrality* implies that rate of energy usage is always less than or equal to rate of harvested energy.

Chapter 2

Related Work

There have been some work in improving the utilization of the battery life, and also in harvesting energy from the ambient sources of energy like wind, solar power, water etc. There have been some successful models which are developed to gather energy from this sources and use if to empower the sensor node. As per our requirements we also need to develop our own node because of our special requirements we have looked in to some of the good models. As the next part of the study requires the development of prediction heuristics which will be used for the energy prediction. We have also studied some related work in this area which we will discuss in detail later in this chapter.

2.1 Energy harvesting models

There have been some researches on harvesting energy from different ambient sources. They have use different ambient sources based on the location of deployment. availability of the energy sources, and We have tried to categories the ambient sources

Energy Source	**Characteristics**
Solar	Ambient, Uncontrollable, Predictable
Wind	Ambient, Uncontrollable, Predictable
RF Energy	Ambient, Partially controllable
Body heat, Exhalation, Breathing and Blood Pressure	Passive human power, Uncontrollable, Unpredictable
Finger motion and Footfalls	Active human power, Fully controllable
Vibrations in indoor environments	Ambient, Uncontrollable, Unpredictable

Table 2.1: Energy Sources

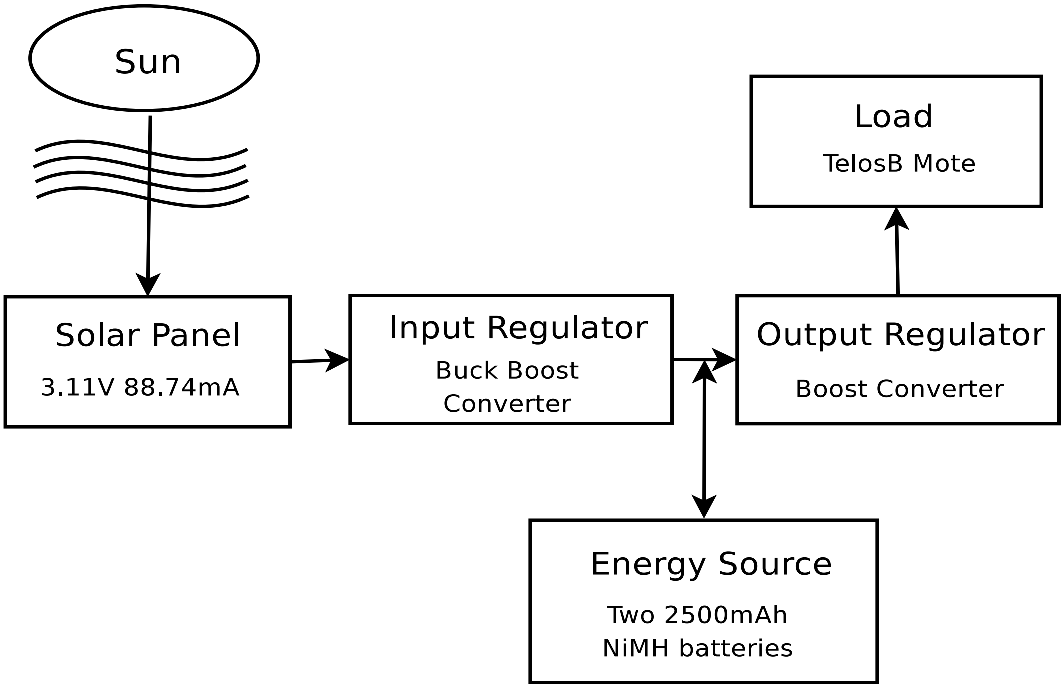

Figure 2.1: Architecture of the Hydrowatch[24] Node.

based on their characteristics, energy availability petter, type of source etc. Table 2.1 gives detailed information about the study. After studying all different models we have chosen solar energy as our interest for collection of energy because of its highly predictability of the availability and also the solar energy is available in ample amount to sustain for longer period. We have studied some of the harvesting sensor node models which are using solar energy as their harvesting module in this section we will look in to them in detail.

2.1.1 Hydrowatch

Hydrowatch is an application setup designed and deployed by Jay Taneja, Jaein Jeong, David Culler at Berkeley for getting the information about the climate changes in the woods. They have also tested the setup in the open ground. They have implemented the system on Telos[1] motes. Figure 2.1 shows the architectural diagram of the Hydrowatch node. Hydrowatch uses a solar panel of area 2.3 inches x 2.3 inches which outputs 88.74mA at a voltage of 3.11V which is used to charge two AA size 2500 mAh capacity NiMH batteries. The batteries are charged by trickle charging method which requires very simple circuit. The input regulator is connected to the solar panel

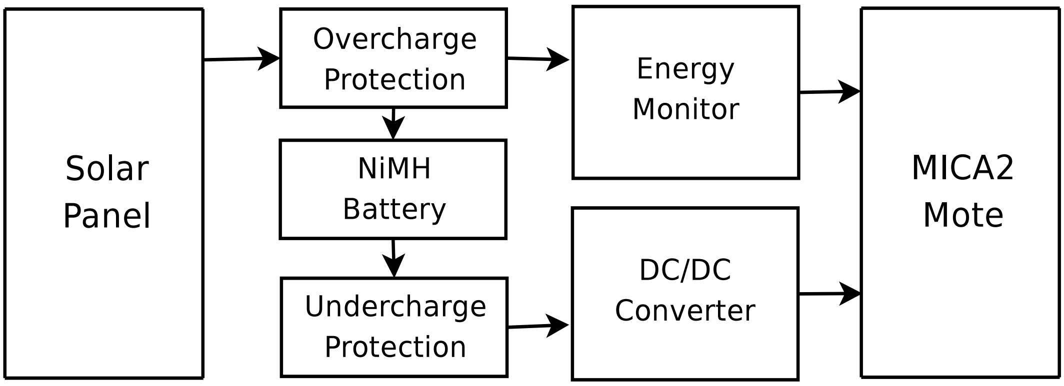

Figure 2.2: Architecture of the Heliomote[21] Node.

which boost-up or buck down the voltages based on the solar panel is giving. Circuit also require some diodes to stop the current flowing in reverse direction when the sun is not present. similarly the boost converter is required to empower the mote from the battery. The Energy collected from the solar panel is measured by the small circuitry. They are using ZXCT1010 in that circuitry for the switching the modes, ZXCT1010 is the current monitor which measures the current passing through the point of interest. They are using it for switching from non-harvesting mode to harvesting mode when the amount of energy gathered from the solar panel is enough to charge the batteries and simultaneously able to run the application load with it. The data are collected of how much energy is collected in a day and how much energy is used in 24 hours. The measurements suggests that the node requires the 79 mWh of energy per day and the least amount of energy which is gathered by one mote should be greater them what is required. Hydrowatch concludes that in normal condition based on the position on the earth and the sun's movement on the sky they can predict the energy that can be gathered by the solar panel and can optimize the parameters.

2.1.2 Heliomote

Heliomote also harvests the energy from the solar panel and uses that for the charging the batteries. Figure 2.2 shows the architecture of the Heliomote node. This model uses a solar panel of area 3.75 inches x 2.5 inches which outputs 60mA at a voltage of 3.3V. They have implemented the system on the Mika2[1] mote. The power from the solar panel is charging 2 NiMH batteries. The undercharging of the NiMH batteries affects the performance of the battery even overcharging of the

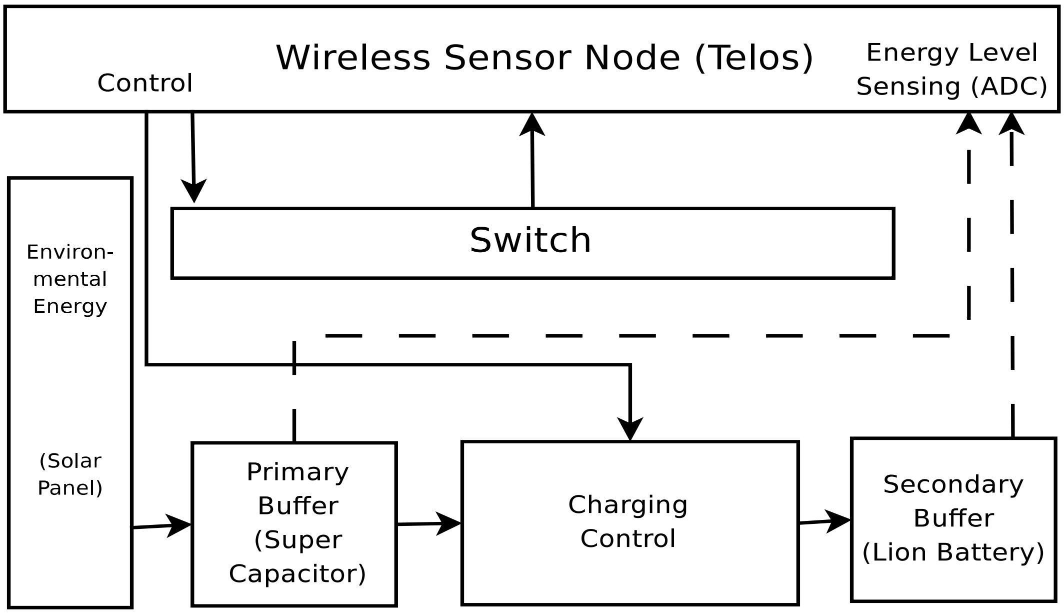

Figure 2.3: Architecture of the Prometheus[10] Node.

battery leads to the battery instability, so they have designed the circuit such that the undercharging the overcharging of the batteries is prevented. That adds the complexity to the circuit but it also increase the life of the node by taking care of the batteries. The mote also measures the energy, the energy monitor keeps checking the energy used and spent. Heliomote paper concludes by the mathematical analysis that if the energy gathered in a unit time is more energy used in a unit time then the node can sustain.

2.1.3 Prometheous

Prometheus is more highly sophisticated design with more improved battery type. The node as shown in Figure 2.3 is having double storage sources. The primary source is a super capacitor which is directly charged from the solar panel. For charging Lion battery needs pulse charge which is very well provided by the capacitors and charging the super capacitor doesn't require any special circuit. So the entire charging circuit is working as follows, The solar panels charges the super capacitors with the highest voltages and current gathered from the sun, when the capacitors are sufficiently charged they sends a pulse of charge which charges the Lion Battery. When the sun is not up in the sky the capacitors are first choice to use the energy from, and when the capacitors are out of charge the mote gets the energy from the secondary source(Lion Battery). This gives the advantage of decreasing the number of the discharge cycles of the secondary battery when there are shadow effect by the clouds where the solar panel is not able to give enough amount of energy to run the application, the charge from the capacitor is used to make the application run normally. While the primary storage source is the capacitor which is having far more number of recharge cycles then that of any battery technology available. The main advantage of the Prometheus node is it is able to achieve the maximize the battery capacity while having the lowest self-discharge rate of the battery, and also the Lion batteries have high power density so the same size of the battery if Lion is able to store more energy from the other types of batteries, so the mote can utilize the maximum effective energy for longer period of time. And the Lion battery is charged from the super capacitor so we can have big capacity battery attached.

2.1.4 Other harvesting models

We have also studied some other good models such as AmbiMax[19], sunflower[23], Everlast[22]. Each of them are state of art models in terms of their charging options, and model design. Ambimax is a super capacitor based node which is its only power storage mechanism. They have tried to over come the problem of high self discharge rate of the capacitors by usage of more then one energy sources to charge the node. The model supports more then one simultaneous energy harvesting sources including solar, wind, thermal, and vibration, each with a different optimal size. So now if there is ample amount of energy to charge the capacitor from multiple sources, theoretical the life of the node is infinite because the capacitor has much more recharge cycles then that of any battery. Sunflower is having one of the smallest size of node with energy harvesting capability. The node is having a remote charging capacity via infrared laser which can charge the critically low powered node from remote and can be saved from dying early. It also has the system level power adaptation system. The hardware design enables the micro-controller to shutdown the sensors and external Flash memory under the control of software to reduce their power dissipation. Everlast is having the node which has the only power storage source as the capacitors. They have tried to over the come to overcome the limited life span of a sensor node by the usage of the capacitor which has more recharge cycles then traditional rechargeable batteries. They also claim to have a better charging mechanism by which the capacitor are charged with the highest possible from the solar cell with the MPPT[1] circuit. They all have different issues with different advantages.

2.1.5 Comparison

From the above study, we conclude that there are many possibilities of the designing of the circuit. The harvesting capacity and the life of the node also changes with the design and the ambient source of energy from which we are harvesting the energy. There are pro and cons of each of the harvesting models that we have discussed. We need to choose the harvesting model which suits best to our deployment criteria.

Hydrowatch is having simplest design of circuit and the solar panel is charging the battery with trickle charging method which is efficient use of the available energy, but the problem with the Hydrowatch is the batteries are hardly utilized by the node application so the batteries goes under shallow discharge cycle which is affecting the battery efficiency over a period of time.

Heliomote overcomes this problem with having the overcharging and undercharging circuit added to the design, but here also the problem remains about the utilization of the battery capacity.

Above two designs has only one battery as the storage so because of this any small fraction of the time when the harvesting is stopping the battery starts discharging which causes that bigger problem. this problem was taken care by the Prometheus paper design they have used two energy storage sources to address this problem. By this design the second battery goes is discharge cycle only when the primary source is completely out of energy.

2.1.6 Conclusion - Harvesting Models

We came to conclusion that the Prometheus charging design is very optimized in terms of energy utilization and maintaining battery efficiency, but it has very complex charging circuit design. Table 2.2 shows the comparison between different battery technologies, we choose to go for NiMH battery as the storage source and design the Hydrowatch circuit is one of the good designs and we are focusing on using the entire deep cycles to utilize the full battery capacity of a recharge cycle the shallow discharging is not problem to us. The selection of ambient source is also a

[1]MPPT - Maximum power point tracking

Technology	**Energy Density** (MJ/kg)	**Power Density** (W/kg)	**Efficiency** (%)	**Discharge Rate** (% per month)	**Recharge Cycles**
Sealed Lead Acid	0.11-0.14	180	70-92	3-4	500-800
Ni-cadmium	0.14-0.22	150	70-90	20	1500
NiMH	0.11-0.29	250-1000	66	20	1000
Li-ion	0.58	1800	99.9	5-10	1200

Table 2.2: Comparison of rechargeable battery technologies

big solution designing criteria, as we have stated earlier the solar energy is the easiest and most suitable energy source to harvest the energy from. We will describe more about the design in the next chapter.

2.2 Energy perdition & Adaptation

As the next part of our study after we developed our H/W device we need to monitor the energy usage from the battery and also the energy harvesting inside the battery. The good study of developing the model for monitoring and logging is provided in the Hydrowatch paper. But we also suppose to adapt to the changes with the energy harvested inside the battery with the energy usage at the node, a good study for adapting the energy usage of the node by changing the duty-cycle is proposed by Kansal[8].

In study of adapting duty-cycle they proposed a energy neutral model for the lower powered energy harvesting sensor nodes. Where they come up with the algorithm for power management that can be used for adapting the performance based on harvested energy information. The algorithm is such that the network achieves the energy neutrality and performs at close to optimal. Their energy prediction model supports the slot by slot adaptation to maximize the overall duty-cycle of entire network.

We are also interested in changing and adapting the energy usage of the node, there are various factors other then duty-cycle that also affects the energy usage at the node. For example changing the rate at which the samples are taken by the sensors, sending multiple sensed values sent in a single big packet, or what we are interested in is by changing the transmit power to send packet. A good study is presented for adapting the transmit power in ATPC[16] paper. In the paper they proposed

ATPC, a lightweight algorithm of Adaptive Transmission Power Control for wireless sensor networks, where each node makes pair with each of the neighbors. With the feedback-based transmission power control algorithm they maintain the individual link quality over the period of time. This model proposes the pairwise adaptation of the transmission power level which saves the waste of extra energy while sending a packet with optimal transmission power level.

Our goal is to adapt the optimal transmit power with the use of energy which is constantly changing by the harvesting model that we have on the node. As we said earlier we are using the transmit power as our factor for changing and adapting the energy usage at the node while the change in transmit power is changed such that the energy neutrality is maintained over the network. In the next chapter we will look in to the design of our node and the algorithms that we have used for the predicting and adapting the energy usage.

Chapter 3

Approach

As our entire areas of interest are divided in to 3 different verticals we have decided to approach them one after another. We have started working on the H/W design and after that using H/W we have gathered different energy profiles that we will see in later part of this chapter, and based on that we have designed our algorithm to adapt the transmit power.

3.1 Harvesting-capable Hardware Design

Prototypes of harvesting-capable sensor nodes already exist Hydrowatch [24], Prometheus[10], Heliomote[21], Everlast, Sunflower, Ambimax etc. Each of these vary in the storage technology used and the charging circuitry. Our hardware prototype borrows ideas from the design of the Hydrowatch [24] node and extends it to simultaneously monitor both harvested and used energy. The node circuit contains the *monitor module* that monitors how much current is passed through it and at what voltage. There are also two zenor diodes in the circuit which controls the current flow of the circuit, and we are using Telos mote for collecting and processing the sensed data. Following description about each module and how it is connected the the circuit. The node is mainly maintaining 3 parts 1) energy harvesting & charging module 2) monitoring module 3) data processing module.

3.1.1 Node Modules

The architecture of the entire node is shown in the Figure 3.1 Energy harvesting and charging module is critical part of the node. It is responsible of the harvesting

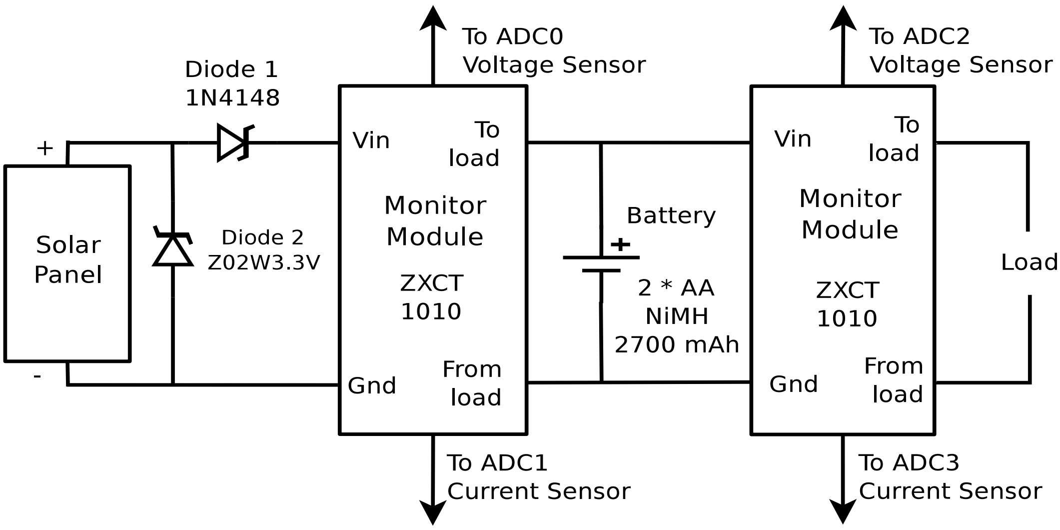

Figure 3.1: Architecture of an energy harvesting node

the energy from the solar panels and charge the batteries. We also need to take care of the batteries that the current doesn't flow in the reverse direction to the solar panel discharging the batteries. Two *AA* 2700 mAh NiMH battery connected to a solar panel via two diodes. Diode 1 (1N4148) is used to prevent reverse current flow, when the battery has higher voltage than that across the solar panel. Diode 2 (Z02W3.3V) is used to prevent the battery from being charged at voltages higher than the battery rating. Monitor module between the solar panel and the batteries monitors the charging rate of the batteries and the monitor module between the batteries and the load monitors the discharging rate of the batteries while the batteries are discharging. We use the ZXCT1010 current monitor chip for logging current and voltage values. Output of the monitor modules is sampled via ADC pins of a Telos mote.

Monitor Module as shown in Figure 3.2, is the component that constantly senses the voltages and current flowing through the circuit. We have used the ZXCT 1010 chip for sensing the current at the point of interest in the circuit. ZXCT 1010 gives the value of current flowing through the load by connecting the V_{sense}[1] resistance to the circuit in series. The current monitor gets the voltages across the V_{sense} and generates the appropriate voltages at the I_{out} point. We can get the voltage at I_{out} point which maps to the appropriate current reading with following equations.

[1] V_{sense} is very low resistance required for operating ZXCT1010.

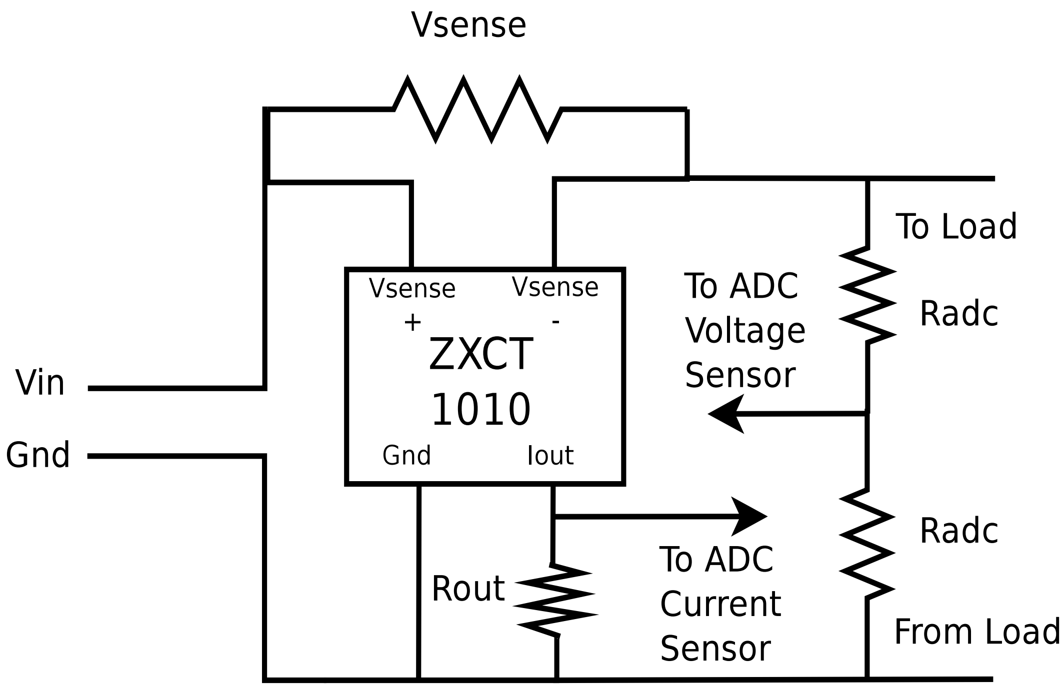

Figure 3.2: Monitor Module

$$V_{sense} = V_{in} - V_{load} \tag{3.1}$$

$$V_{out} = 0.01 \times V_{sense} \times R_{out} \tag{3.2}$$

$$V_{sense} = I_{sense} \times R_{sense} \tag{3.3}$$

Here the values of V_{sense} and R_{out} can be selected as per our requirements of the voltage range. Here 0.01 value in the second equation is the because of the internal 100Ω resistance. We have chosen R_{sense} as 0.1Ω to decrease the series resistance as minimum as possible so that there is not much power loss in the monitoring circuit. We choose R_{out} as 1000Ω so when ever the current passes through the circuit and we get equivalent voltage at the I_{out} by applying the Formula 3.1, we can get the I_{sense} value which is the current passes through the load because R_{sense} is in series with the load. The voltage across the load can also be measured by getting the voltage difference between the to points of the load. As the maximum voltage range that can be measured by the the Telos mote is 2.5 V, We have connected the R_{adc} as 1000Ω resistance parallel to the load and measured the voltage difference from the middle of the two resistors and ground and then doubled the value to get the actual voltage.

There are two Monitor Modules as the part of the charging circuit where one of the module is connected between the solar panel and the batteries and the second module is connected between the batteries and the load. The first module is collecting data of the current and the voltages as what the charging is done at the time sun is up in the sky and based on that we can calculate the amount of energy gathered from the solar panel to the batteries. The second module is collecting the data of the energy which is used by the load from the batteries or from the solar panel. So by taking the difference of the both the energy calculations we can calculate the actual amount of the energy the batteries have at any particular instance of time.

We are using Telosb[1] mote as the processing module. Telos is an ultra low power wireless sensor module for research and experimentation. Telos is the latest in a line of motes developed by UC Berkeley to enable wireless sensor network (WSN) research. Telos' new design consists of three major goals to enable experimentation: minimal power consumption, easy to use, and increased software and hardware robustness. The hardware components are selected and integrated in order to achieve these goals. The mote is having Texas Instruments MSP430 micro-controller, Chipcon IEEE 802.15.4-compliant radio, and USB for interfacing. We are using the ADC pins for getting the data from the *Monitor Module*. The ADC pins are used for collecting the voltage and current readings from the circuit as the voltage difference between ground pin and ADC pins. We have done measurements for generating the energy profiles, so we have used very simple setup for the implementation and generating the required data. We will look in to the energy profiles in the let part of this chapter. So we have used two Telosb motes one mote is sensing the data from the sensors via ADC channels and sends that to base-station which is one more mote connected to the server collecting and logging the data on a computer.

3.1.2 Solar Panels

A photo-voltaic module or solar panel is a packaged interconnected assembly of photo-voltaic cells, also known as solar cells. Solar Panels use light energy (photons) from the sun to generate electricity through photo-voltaic effect. The electrical connections can be made in series to achieve a desired output voltage and/or in parallel to provide a desired amount of current source capability from the solar panel. There are 3 different kind of the solar panels, mono-crystalline solar panels, polycrystalline solar panels and amorphous solar panels. We are using amorphous solar panels for

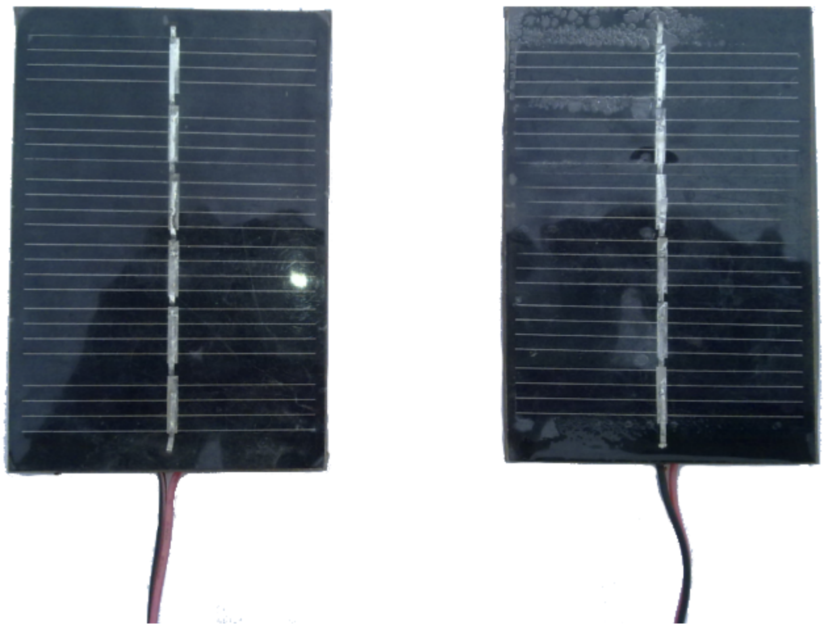

Figure 3.3: Solar Panels modules (GESPM01)

our study. These types of solar panels have lower efficiency then the other two types of solar panels but they are the cheapest to produce, and the one and most important advantage of amorphous solar panels over the other two is that they are shadow protected. That means that the solar panel continues to charge while part of the solar panel cells are in a shadow. Our initial experiments uses two VEGAKIT[2] modules of the solar panel of type GESPM01 of size 3.25 inch × 2.25 inch whose ratings are 3V / 150mA, V_{oc}[3] is 3.6V and I_{sc}[4] is 165mA. Figure 3.3 shows the solar panels that we have used.

3.1.3 Battery

We have used the NiMH batteries as our storage medium. As we said earlier we have used this technology because of its trickle recharging capability where we can recharge the battery with even lower charging rates. Here trickle charging means we

[2] www.vegakitindia.com
[3] Open Circuit Voltage
[4] Closed Circuit Current

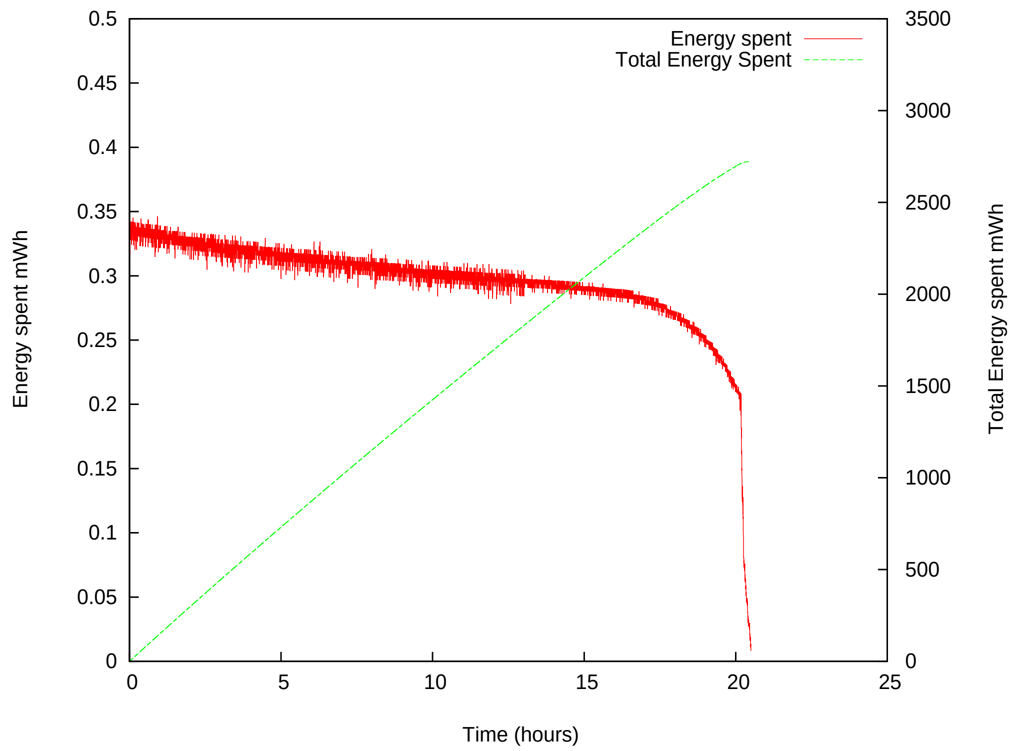

Figure 3.4: Discharging of the Battery

are not disconnecting the recharging circuit when there is no recharge opportunity and its is constantly connected to the batteries. So whenever the charging opportunity is available the batteries are getting charged without any waste of energy and time. We are showing not fully charged two AA NiMH 2700mAh battery's potential in Figure 3.4. You can see that the battery able to give its highest performance rating till they dies keeping the voltage as high as 2.5V. and then suddenly when the voltage goes down to 1V the current dissipation goes down. So we can say that the battery will perform better till it completely dies giving highest performance. We have calculate the amount of energy the batteries still able to give is 2700 mWh after around 20 hours of slow discharge.

3.2 Module Energy Metering & Benchmarking

As we have built the node we have performed some initial experiments for verifying the different components of the circuit. We ave also built one small circuit to characterize the solar panels as shown in Figure 3.5. As our requirement of the

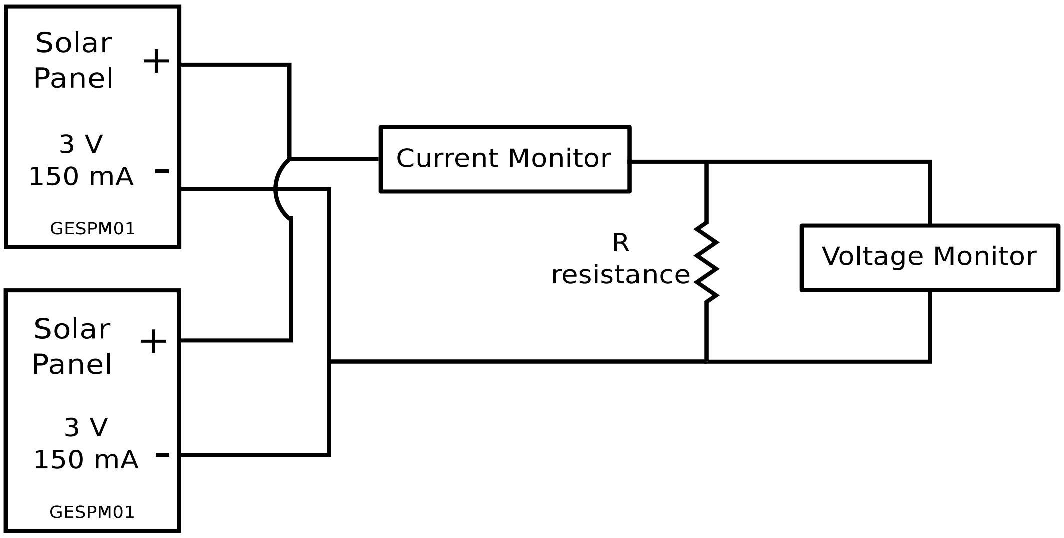

Figure 3.5: Setup for characterizing solar panel.

voltages is matching with the solar panel voltages we have connected the panels in parallel so that they gives the voltage as 3V but gives the total current collected from both the panels. The characteristics of the panel is generated by plotting the voltages Vs Current graph as shown in Figure 4.1. This plot gives the verification about the ratings which are given by the company. We have got this configurations by doing an simple experiment on the solar panel.

We have connected the solar panels in parallel to get the maximum current possible from the panels keeping the voltage at 3V. we are sensing the voltages and current with the circuit that we have built for taking the measurements of the energy. The X axis of the graph is current generated from the circuit at a particular time and Y axis is the voltage. From the Figure 3.5 when we increase the resistance R, by going short circuit to open circuit we get different voltage and current from the solar penal. The plot conforms that the we can get the maximum voltage 3V from the solar panel and as the ZXCT 1010 has the limitation that it can not measure the voltages bellow 1.25 V. For getting the correct results we have performed the experiments only from 1.5V to maximum voltage given by the solar panel. We can see from the graph that the solar panel is generating the 320 mA current at 1.5V and if we extend the graph further it will reach to 330 mA which is expected. There is one more characteristic of the solar panel is the MPP[5], Which tells the maximum power that can be generated from the solar panels, and we can built the intelligent circuit for keeping the circuit

[5]Maximum Power Point

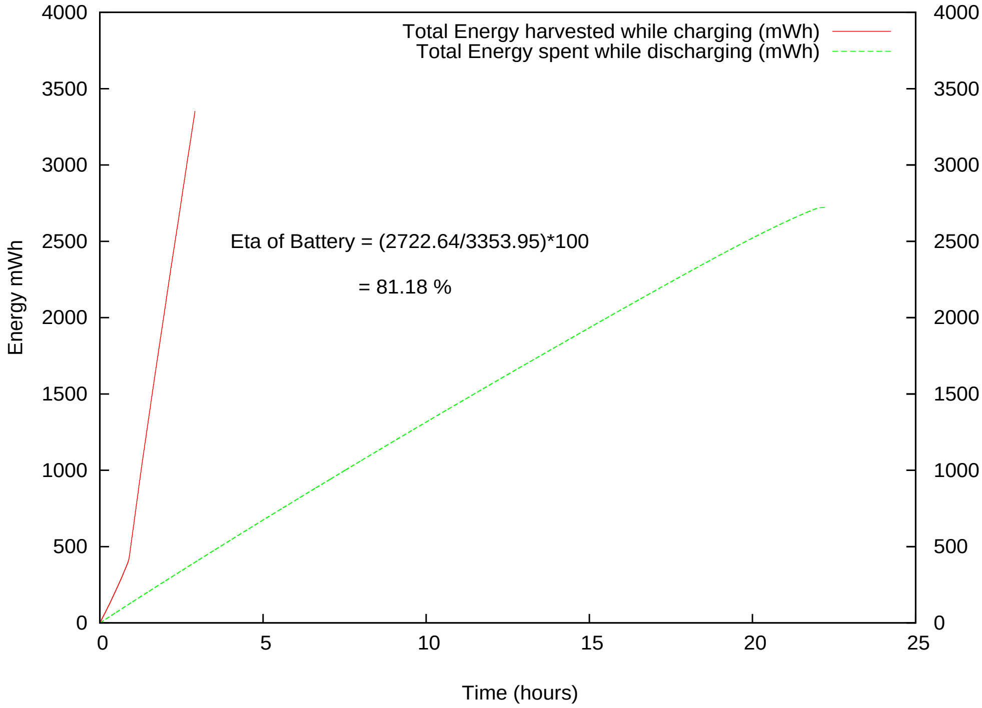

Figure 3.6: *AA* 2700 mAh NiMH Bettery Efficiency.

working on MPP, but we have not implemented that for our part of study, certainly we can implement MPPT[6] in the future part of this work.

Based on the logs which we get from the sensor nodes we can calculate the energy generated from the solar panel and used by the load. From the Figure 3.1 we can see that the ADC0 and ADC1 pins are collecting the data that how much energy is harvested from the solar panel and the ADC6 and ADC7 pins are collecting the data about how much data are being use by the load. So by getting this information. we can calculate the amount of energy collected in the batteries at any particular instance of time. generally energy is calculated in the kWh units but as we have the energy generated in very low values we will be measuring the energy in mWh. As the V-I graph says that we are getting the current in mA and voltages in V, following is the equation for calculating the energy from the data.

$$Energy(mWh) = \frac{Voltage(V) \times Current(mA) \times Time(s)}{3600} \quad (3.4)$$

[6]Maximal Power Point Tracking

From this equation we can calculate the amount of energy generated by the solar panels and amount of energy use by the load so by the difference we can get the amount of energy stored in the batteries. The main purposes of energy metering and this experiment was that we need to determine efficiency of the battery because battery efficiency has an implication on estimation of energy available at a node. For this, we charge the battery to different levels and then discharge it completely and determine the input and output energy ratio(efficiency) of the battery. Based on the experiments the efficiency(η) of the battery used in our prototype is estimated to be 81.18%. Figure 3.6 shows the results that we got from our small experiment where we have charged the batteries monitoring the amount of energy used to charge the completely discharged batteries and then discharge them completely while monitoring the amount of energy available from the batteries as a usable energy.

3.3 Energy Prediction

The energy graph can be plotted of a period of a day for getting the results of how much of energy is generated and used by the load in a day and this pattern repeats with minor correction over period of time with the change in the seasons. The amount of energy generated from the same solar panels also changes with geographical location of the deployment. There are also other factors affects the energy gathering from the solar panel. The weather conditions - in a sunny day you will be getting the maximum amount of energy but in cloudy weather the amount of energy gathered decreases. The Hydrowatch paper points out results by saying that in a fairly cloudy day the node in the woods gets more energy then that of the sunny day because of the diffusion effect. The orientation of the solar panel also affects the energy gathering. the dust on the solar panel and if the one of the solar panel connected in series connection gets damaged makes big impact on the amount of energy generated by the solar panel.

Figure 3.7 shows a sample current and voltage profile collected on 5^{th} May, 2010 on CSE Department terrace. The profile was generated using our hardware prototype. The solar energy harvesting sensor node is kept on a terrace floor which is on such a height that noting is blocking the sunlight from the sunrise to sunset. As can been seen from the figure, harvesting opportunity begins at around 7 AM (just after sunrise) and lasts till around 6 AM(till sunset) The maximum current

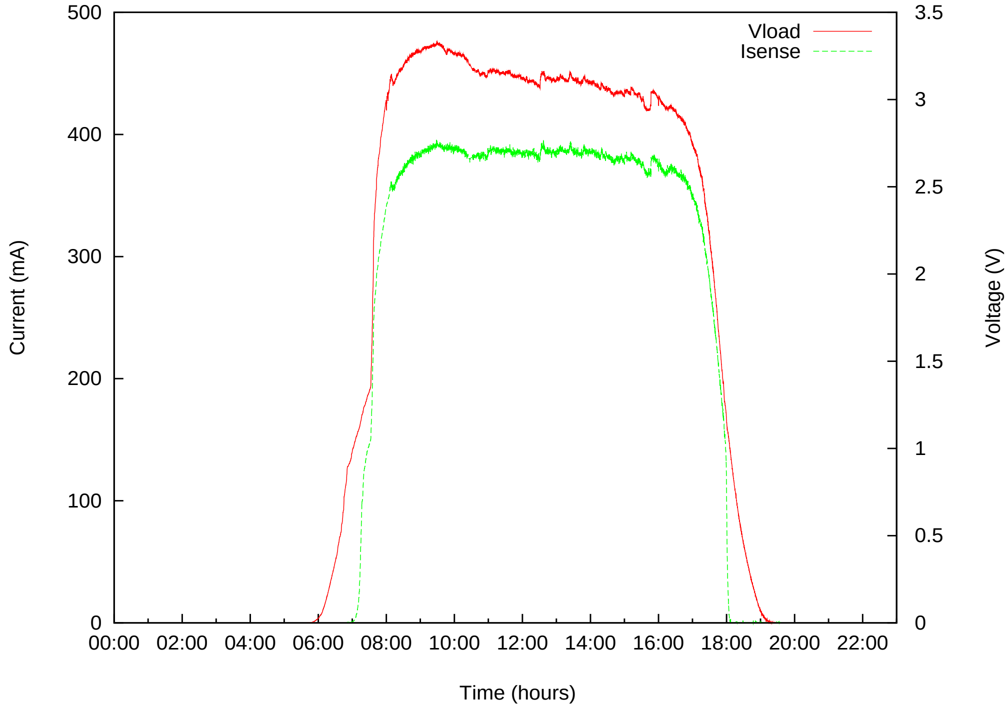

Figure 3.7: Energy profile collected at CSE Dept. terrace.

of close to 580 mA at 3 volts. Total energy harvested from the panel is 11595.25 mWh. Figure 3.7 shows the energy profile that we have collected. Here the X-axis shows the time of the day at the time when the amount energy is available. They Y-axis shows the amount of energy collected at that particular time of the day, We have collected each sample at every second and we logged the average of every 7 seconds readings to minimize the number of readings per day and the also to decrease the no of communication needed to do to send the sensed data. We have collected several such energy availability profiles at different types of locations—rooftop, indoor environments, close to windows, inside foliages etc. We plan to release the multi-day, multi-location traces for use as inputs for testing harvesting-aware solutions with simulators/emulators.

As we know that the energy availability rate from the sun follows the same pattern every day. We can predict that the every day the amount of energy harvested from the sun will be almost the same. Also we can say that the amount of energy harvested at the particular time period in a day will also not change in two consecutive days. There also one more observation that some time there are foggy environment so that the diffusion of the solar rays decreases the amount of energy harvested but still the ratio of the amount of energy harvested in two consecutive slots doesn't change much in two consecutive days. Here for better prediction we have divided the entire day in number of slots, where each slot is of 10 minutes. We have divided the slot in 10 minutes because of the slot is small enough such that the sun's position doesn't change much in span of 10 minutes, so we can have better expected results. And also it is big enough so that we don't need more communication overhead to distribute the latest information. So now we have divided the entire day in the 144 slots and we are predicting the amount energy gathered of entire day in slot by slot bases. Based on our above assumptions we have designed our prediction model as follows.

$$E_k^p = \frac{E_{k-1}^a \times E_k^h}{E_{k-1}^h} \tag{3.5}$$

$$E_k^h = [(1-\alpha) \times E_k^h] + [\alpha \times E_k^a] \tag{3.6}$$

Where E_k^p is the predicted energy availability in slot k, E_k^a is the actual energy available in a slot and E_k^h is the historical average energy available in a slot. We update the historical average based on a weighted average of the current estimate and the actual energy available. The parameter α can be used bias past or current readings and can be used to capture long-term changes in energy availability profiles. But as we have performed the experiments and the try to apply the model to the data we found that the energy availability in the slots is not only depend on the two slots of current and profile days data but also solely depends on the current slot of the profile so we come up with the more corrective and improved prediction model as follows.

$$E_k^p = [(1-\beta) \times \frac{E_{k-1}^a \times E_k^h}{E_{k-1}^h}] + [\beta \times E_k^a] \tag{3.7}$$

$$E_k^h = [(1-\alpha) \times E_k^h] + [\alpha \times E_k^a] \tag{3.8}$$

Here we have corrected the model by giving the weighted to the historical data and the todays' previous slot energy collection. By the experiments we have come to know that the β needs to be close to 0.5. It means that by giving both, historical data and the previous slot collected energy data, equal weight we are able to minimize the error. We will see the results in the next chapter.

3.3.1 Algorithm for transmit power control

The optimization of the energy consumption can be done by changing many parameter of the wireless communication components. We have chosen the transmit power because the majority of the power consumptions is done by the radio via transmitting the messages. Based on the predicted energy for a slot, the battery efficiency and the current capacity of the battery, the *effective* energy at a node can be estimated that we have seen in previous section. Our goal is to tune the transmit power of a node based on its dynamically changing effective energy. Traditional power control algorithms, dealing with finite battery nodes, always aim to minimize a function of non-increasing residual energy over all nodes. With recharging opportunities, batteries get recharged and power control can potentially be concerned only for the duration between recharge cycles. This relaxation can be exploited to operate at higher transmit powers than one that is based on a energy-usage minimization function. Our aim is to propose a formulation which can capture duration and magnitude of energy availability and determine dynamic transmit power settings.

We are trying the adapt the transmit power for saving energy at network level and utilizing the energy of the highly powered node efficiently. We can identify that while changing the transmit power the neighborhood will be changing dynamically so we need to manage and stabilize the network for efficient routing of the packets. We also need to make sure that the change in transmit power also changes the number of paths to the destination so the path is chosen efficiently such that the network doesn't get disconnected. The nodes are sending packets are using their energy, we also need to take care that the selection of the path is such that the each node of the path has enough energy to sustain till the next recharge cycle. Tacking care of all this situation we are proposing the following solution to the adaptive power control problem.

Consider a network of N nodes. Where each node has the harvesting potential and also have the storage batteries. We assume that for some initial time period the harvesting facility is enough that the batteries can be fully recharged. We assume that the nodes have more then one transmit power levels which we can set by the software implementation and each of the node is fully connected to more then one nodes when the transmit power is kept at half of the highest possible level. Our main goal is to maximize the average transmit power level at each node such that every node survives till the next recharge cycle and also uses minimum amount of battery

Txpower level	Current Energy level	[Nodes Connected	Min No. of hops to reach sink]

Table 3.1: Beacon packet format.

Algorithm 1 Select the maximum transmit power level for a slot.

Require: $E_{Tx}[level]$, P_{send}, E_{slot}
Ensure: $[N_{select}]^{max}$
  $E_{packet} \Leftarrow E_{slot}/P_{send}$ {Per packet estimated energy }
  while $N < level$ **do**
    if $E_{packet} \leq E_{Tx}[N]$ **then**
      $N_{select} \Leftarrow N$ {Finding maximum transmit power level able to send all the packets}
    end if
  end while

capacity. Our algorithm is divided in two steps.

The entire procedure is divide in two steps, neighbor initialization and after stabilized network choosing transmit power based on current status. At the start of the first stage each of the nodes beacons and broadcasts the transmit power information and the energy levels to all the neighbors. The beaconing is started by the sink node and it gets flooded to the leaf nodes. All the nodes updates their routing table and sends the information to the next node. We have shown the beacon format in the Table 3.1, here the last fields *Nodes connected* and *Min. no of hops to the sink* are updated by each node and only sent in the last beacon and shows the information about the reachability to the sink with one minimum hop count from that node. All the nodes listening to the every broadcast records and generates the customized routing table that we will be showing later in this section. This initialization step is performed only once when any new deployment starts, after this initialization step each node of the network has at least one path to the sink. We are assuming that due to the homogeneous environment properties if a node is able to receive a beacon from some node at certain transmit power level the receiver node is also reachable to the sender node with the same transmit power level, as we have all the node same with the characteristic.

The second part is about selecting the proper transmit power level for the sending the packet. Here we are not interested in the routing layer decisions of choosing the next node. Our goal here is to set the transmit power level, by doing so the node's transmission range increases and we assume that the number of connected nodes also increases, So now we have better choice for selecting the shorter route to sink. The algorithm 1 used for selecting the transmit power level suitable for the particular slot.

We acknoledge that there will be many implecations by changing the tranmit power level of the node to the communication of the entire network. As we are changing the tranmit power the network topology will change dynamically as we increase the tranmitpower the node's tranmission range increases and it may be able to communicate with more nodes then earlier. This will change the neighbourhood of the node so effectively the routing table will have to go under changes. If the node's tranmission power flutuates all the time the raouting table will never stabilize and it will create the overhead of more control message communication and effectively waste of energy. It will also cause the change in the energy consumption rate of the battery because the more tranmit power means more energy usage, and if the energy usage not stabilize it will also effect in the life of the bettery on a longer run. Also it will cause problems in the efficiency of the adatation algorithm because the algorithm1 has the component E_{slot} which is depend on the current bettery capacity and the remaining time of the next recharge cycle so if in every slot the battery consumption rate flutuates it will cause change in the parameter. As we know that as the transmission rage increases the less intermediate nodes are reqires to forwared the packet to the destination. So by using the more energy of the nodes, which are having enough energy to survive till the next recharge, we are trying to minimize the energy consumption of the nodes which are haveing less energy to forwared the packets. Some times for minimizing the energy consumption rate we choose the minimum power level. So there may bo some condition arrises that all the leaf nodes send the packets through an intermediate node and the node looses its energy rapidly and not able to survive long even if the leaf nodes are having enough energy to send the packets directly to the next node by skipping the few intermediate nodes. Here our intution is that if the node has extra bettery capacity remaining at the start of next recharge cycle it can be considered waste of energy because by the end of recharge cycle we assueme that the nodes will be fully charged. Now as we increase the tranmission power it also increases the tranmission range of the node it also increases the interference range of the node. Also it will casue some latency because of the more busy medium all the time but as we know that the no of packets to send in a perticular time period are not high so higher interference range and the delay because of busy medium is not an issue of us.

Chapter 4

Evaluation & Experimentation

We have started with the

4.0.2 Solar Panel Bechmarking

4.0.3 Battery measurements

As we are using the rechargeable NiMH 1.2V batteries of capacity 2050mAh each. We have preformed the experiment for checking the total energy that can be stored in the batteries. For getting the total capacity of the batteries we have charged the batteries from the normal charger having the overcharging protection. After keeping the batteries for charging about 10 hrs we have kept them for 1 day for best performance. After that we have connected the 35 ohm of the resistance and collected the voltage and current from the basic current monitor circuit that we built and plotted the energy. Figure 8 gives data collected from the sensors. The graph shows that the batteries can give the 2.5 V, because of the connected in series, for entire period of the time when the batteries are discharged then the voltage goes down to the 1 voltage, which is the characteristics of the NiMH batteries.

4.0.4 Solar Panel on the window facing the sunset.

The experiment is performed at the window facing the west side so we will not be able to get any sunlight until afternoon, the experiment shows that we will get the immediate increase in the current when the sun rays falls on the solar panel and then when the time passes by the current value decreases with the time but still the voltage remains above 2.7V even when we are getting very low current. The spikes in the

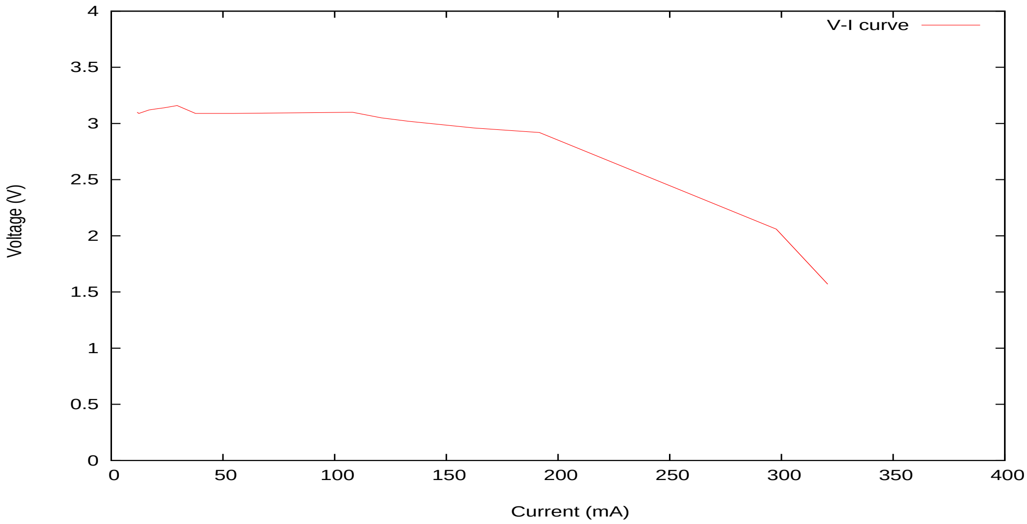

Figure 4.1: Characteristic of Solar panels Used.

experiment results are because of the few clouds. When ever the cloud covers the sun there is sudden decrease in the current we are not facing any shadow effect here because there is no spot lighting happening the window is widely facing the sun after the noon till the sun set. At the end of the day we are able to get around 1600 mWh of energy harvested from the solar panel to the batteries, which is near to the total amount of energy gathered in a day by the highest gathering node of the Hydrowatch paper. From this we can say that we have got the correct readings because the highest amount of the current they are getting at the same voltage is 80 mA while we are able to get 250 mA at the noon.

4.0.5 Experiences with the Experiments

Following are some experiences which we would like to share with designing the H/W and measurements with solar panel.

- We have started our approach by designing the circuit of the current monitor and then expanded it to the charging circuit. Our main goal to design the current monitor is to get the current ratings in the voltage reference because the ADC pins of the Telos mote can only sense the voltage difference with reference to the Gnd pin on the Telosb mote. So we choose ZXCT 1010 as the current sensors.
- There were also issues with the selection of the Rsense and the Rout for getting

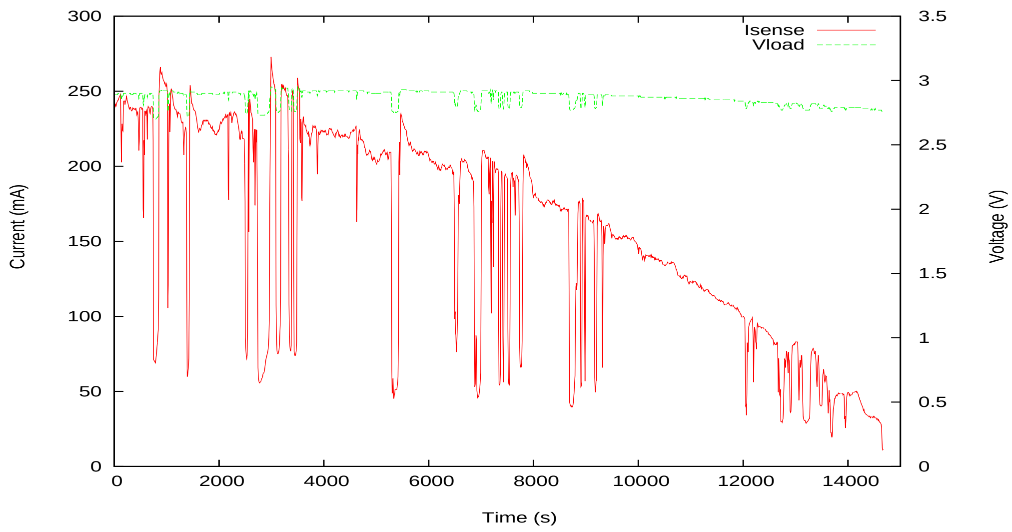

Figure 4.2: Window facing west side of the building - voltage and current.

the correct readings and maintaining the highest efficiency of the because the more energy wested in the monitoring the less energy we get for the actual application.

- When the current is not flowing from the solar panel the reverse flow flows from the batteries at this time we will get the voltage readings across the load but the current readings will be zero because ZXCT doesn't give output the Iout if the current is flowing in reverse direction.

4.1 Experimental Methodology

4.1.1 Solarpanel

characteristic of solar panel

4.1.2 Battery Experimentation

Finding Eta of Battery.

4.1.3 energy profiles

- On terrace

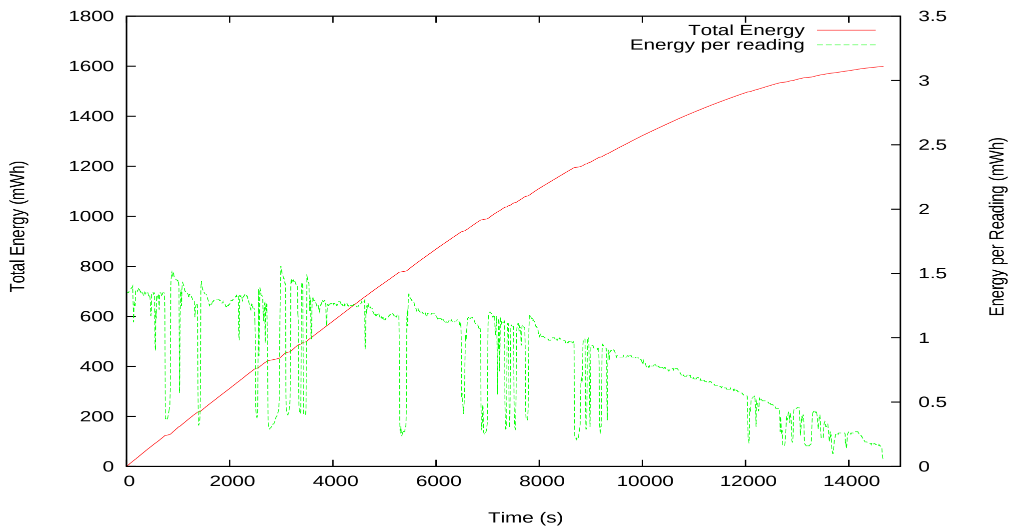

Figure 4.3: Window facing west side of the building - Energy

  – With clouds
  – without clouds
  – comparison of energy

- On sunrise side
- On sunset side
- blocked from both side
- comparison of all in terms of availability of energy at the end of day.

4.2 Energy profile generation

4.2.1 evolution of profile

4.3 prediction accuracy

4.3.1 comparison

4.4 Discussion

Chapter 5

Conclusion

As part of this work, we aim to exploit the availability of periodic energy harvesting opportunities to tune node-level transmit power. Towards this, we identified three main solution components, (i) harvesting-capable hardware prototype, (ii) accurate energy metering and prediction and (iii) formulation of a harvesting-aware transmit power control problem and its solution. We presented the design of our hardware prototype and demonstrated its use to collect energy profiles for harvesting. Further, we presented a simple model to predict available energy and presented an initial result of its applicability. As part of future work, we plan to, (i) extensively collect energy profile logs, (ii) compare and evaluate energy prediction models and (iii) formulate and solve the transmit power control problem.

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