BACHELOR OF SCIENCE IN COMPUTER SCIENCE
AND ENGINEERING

Energy-Adaptive Routing
in
Energy-Harvesting Wireless Sensor Networks

by

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Abstract

Wireless sensor networks are unique networks which is easily characterized by their limited power supply, ubiquitous networking and deployment of remote and hostile area. The applications of wireless sensor networks comprise a wide variety of scenarios. Energy is a main issue in wireless sensor networks (WSN) that function on limited power supplies like batteries. Efficient energy utilization is a promising area of research now-a-days. Recent advances in wireless sensor networks have led to many new routing protocols specifically designed for sensor networks where energy awareness is an essential design issue. Energy harvesting technique has prolonged the lifetime of the network but it can't ensure perpetual network Lifetime of the network. Significant role of route selection strategy in assurance of perpetual network operation in EH-WSNs has inspired us to design an efficient routing for EH-WSNs to meet desired objective. Assurance of both maximized network remaining energy and balanced energy depletion are two promising requisites to have perpetual network operation. Our proposed routing consists of a set of efficient routing metrics with an adaptive protocol compatible with this metric called Energy Adaptive Routing (EAR) minimizes the wastage of energy in network with minimum overhead and maximizes the total network remaining energy. Simulation results show that EAR greatly outperforms other routing metrics and protocols in the challenging EH-WSN environment. We propose a routing for periodic environment where route will take decision distributively and choose route with a probabilistic model. Rapid degradation of best path has overcome here and maintain a perpetual network lifetime.

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Declaration of Authorship

This is to certify that the work presented in this thesis is the outcome of the analysis and investigation carried out by Kayes Ahmad Khan and Mahbubul Alam Palash under the supervision of Prof. Dr. Mohammad Mahbub Alam in the Department of Computer Science and Engineering (CSE), IUT, Dhaka, Bangladesh. We are also declared that neither of this thesis nor any part of this thesis has been submitted anywhere else for any degree or diploma. Information derived from the published and unpublished work of others has been acknowledged in the text and a list of references is given.

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Chapter 1

Introduction

1.1 Introduction

In this chapter, we present a basic outline of our thesis including problem definition. Then we include our thesis objectives and contributions. At the end of the chapter, we provide a short description of the organization of the thesis.

1.2 Background

1.2.1 Wireless Sensor Network

Wireless sensor networks (WSN) have become a preferred solution to a broad range of wireless communication challenges for various applications, from large, spatially distributed systems like the smart grid, to power-hungry applications such as video surveillance.Energy limitation is a major challenge which has been addressed many times in the context of wireless sensor networks. Wireless sensor networks (WSNs) provide long term and low cost solution to many emerging applications including surveillance [1] [2], precision agriculture , environmental , machine and structural health monitoring etc. Traditionally, sensor devices are equipped with chemical batteries having a limited lifespan . Even with efficient energy conserving mechanisms, the battery would eventually drain out and the network dies . So, the performance of WSNs depends on the capacity of power sources. Researches on WSNs mostly pay attention on maximizing the lifetime of the network. Generally, a WSN is composed of a large number of static sensor nodes with low processing and limited power capabilities that often communicate over unreliable, short-range radio links.

Although the battery technology has come a long way since its birth, it is not to meet ever increasing demand of WSN. For this reason, researchers and techno-giant companies were seeking proficient systems able to extract necessary energy from ambient sources. The advance of energy harvesting circuits has enabled the possibility to convert and store solar energy efficiently. It gives a new direction of research for maximizing the network lifetime is arming the sensor devices with small renewable energy harvesters and capacitors [3], giving birth to energy harvesting wireless sensor networks (EH-WSNs).

1.2.2 Energy Harvesting

Energy harvesting is a process of capturing and converting ambient energy into usable electrical energy. A large number of external energy sources have potential to be harvested [4].

- Natural energy, e.g. wind, water flow, ocean currents, and the sun.
- Mechanical energy, e.g. vibration and mechanical stress and strain.
- Thermal energy, e.g. waste energy from furnaces, heaters, and friction.
- Light energy, e.g. natural and artificial light.
- Energy from other sources, such as chemical and biological sources.

1.2.3 Energy Harvesting Wireless Sensor Node

Energy Harvesting-based WSNs (EH-WSNs) are the result of endowing WSN nodes with the capability of extracting energy from the surrounding environment. Energy harvesting can exploit different sources of energy, such as solar power, wind, mechanical vibrations, temperature variations, magnetic fields, etc. Continuously providing energy, and storing it for future use, energy harvesting subsystems enable WSN nodes to last potentially for ever. This technology has made it possible for sensor nodes to rely solely on energy harvesting devices for power. Every sensor node usually has one or more energy harvesters, an energy storage device (e.g., super capacitor) to store the harvested energy, a sensor for measurement, a micro-controller for processing and a transceiver for communication.

The sink in EH-WSN is assumed to have infinite power or connected to the power mains.

Key differences of hardware structure between battery-powered WSNs node and EH-WSNs node is on the energy supplement module. These differences introduce some unique characteristics for EH-WSNs.

- Energy in EH-WSN is potentially infinite. If some energy usage plan is applied it can serve for a long time. For an example, solar based WSN can harvest energy from the sun every day and remain alive for a long time.
- Energy distribution is not even. Most of the networks are deployed in hostile environment. For that some of the node will harvest more others depending on the causes.
- EH-WSNs are very much sensitive to environment. For energy it depends on the environment. So, temperature, humidity etc. play a vital role on node lifespan.

1.2.4 EH-WSN Applications

EH-WSNs have created a new era in WSN applications. As it has infinite lifetime, many of the sophisticated applications are based on it. It has drawn a lot of attractions to the researchers and engineers. Some of its applications are:

- Area monitoring
- Environmental/Earth sensing
- Air pollution monitoring
- Forest fire detection
- Landslide detection
- Water quality monitoring
- Natural disaster prevention

1.3 EH-WSN Research Goal

The performance of EH-WSN largely depends on the perpetual operation of the sensor nodes. Temporary death of certain nodes creates discontinuation in communication process and deteriorate overall network performance. Therefore, the ultimate objective of communication protocols on EH-WSNs includes the assurance of *perpetual network operation*. Since routing strategy significantly influences the energy state in network, thus this becomes a critical issue in EH-WSNs which need to be handled efficiently. Routing strategy takes substantial role in minimizing energy consumption as well as balancing energy depletion in EH-WSNs. Hence, a proactive and harvest aware routing strategy can take prominent role in assurance of perpetual network operation in EH-WSNs. A routing strategy mainly consists of two parts:

- Routing Protocol
- Routing Metric

1.4 Routing Protocol

A routing protocol specifies how routers communicate with each other, disseminating information that enables them to select routes between any two nodes on a computer network. The selection procedure of any routing protocol is on the basis of route selection strategy or routing metric

1.5 Routing Metric

A routing metric is a unit calculated by a routing protocol for selecting or rejecting a routing path for transferring data/traffic. Such unit can be number of hop , expected number of transmission count etc. However, for the satisfaction of certain energy objective of EH-WSN, its routing metric should be aimed at

1. Minimizing the Energy Consumption in network
2. Ensuring the Perpetual Network Operation
3. Balancing the Energy Depletion

Moreover, the stochastic nature of ambient power sources implies the significance of appropriate use of harvested energy in such networks.

1.6 Problem Statement

Existing routing schemes in EH-WSNs consider a set of properties associated with energy harvesting nodes and networks. Among them

- Node residual energy
- Predicted harvest energy
- Estimated energy consumption
- Channel condition

are mentionable. Undoubtedly, for the assurance of perpetual operation all of these components carry significant importance in directing any route. However, at the presence of significant ambient energy source the overcharge of limited capacity battery is not very unusual. Which is the amount of energy produced from battery overcharge of limited capacity battery, which is suppose to be lost unless used. Such loss of energy due to overcharge on fixed-capacity batteries is referred as wastage of energy. Hence, minimization of such wastage will be an optimal solution to maximize the total network remaining energy as well as ensuring perpetual network operation. Again, there are few researches on Proactive routing in EH-WSN field. There is no such metric which is adaptive in periodic nature.

A very recent work published in 2014 [5],[17]includes the amount of wasted energy in their route selection consideration. Minimization of the cost associated with the energy consumption due to packet transmission and the total network energy wastage due to battery overcharge are two components of their proposed routing metric, named wastage aware routing metric. With the prime goal of maximizing total network resulting energy, [5],[17] chooses a route $\Phi_n \epsilon \sigma$ among a set of routes from same source to sink which ensures the minimum total network energy wastage and transmission cost. The consideration of total network energy wastage in route selection mechanism can definitely leads to maximized total residual network energy. Another recent works of [23] proposes a routing metric FED that met all the goals to achieve a perpetual network operation. But a routing metric is not sufficient to achieve complete perpetuality and a higher throughput.

However, this metric is not suitable for heterogeneous network rather it works in homogeneous network. Again, there is no threshold voltage limit there to save the weaker nodes.

Another thing is there may be huge degradation of best path due to over traffic flow.That causes a network partition which is not acceptable at all. We put two threshold voltage limit to prevent the network partition. One threshold will stop the transmitting data from other nodes and last threshold will force down to sleep the node.

Along with the routing metric we need an adaptive routing protocol that will be suitable for our metric and ensure the goals of our thesis work. In existing EH-WSN research there is no routing metric used in proactive routing protocol. There are many reactive routing protocol like AODV,DSR, Directed Diffussion. CTP is a well known Proactive routing protocol. But CTP is not designed for EH-WSN environment.So,we have designed a proactive routing protocol for EH-WSN environment very much adaptive with our routing metric.

1.7 Thesis Objective

In this thesis work, we focus on designing a routing for EH-WSN with the objective of

1. Minimizing the Energy Consumption in Network.
2. Acquiring a Balanced Position between
   (a) Minimization of Energy Consumption and Maximization of Minimum Energy Levels
3. Working on heterogeneous network
4. Adaptive with proactive nature
5. Rapid degradation of best path
6. Assurance of above goals involving minimum overhead.

1.8 Thesis Contribution

The primary Contributions of this thesis are stated below:

1. Performance evaluation of On-Demand Routing Protocols in Real Test-Bed environment. (TelosB-Mote)

2. We have modified proposed PFED metric in [23]. We have upgraded in for heterogeneous network

3. Put two threshold energy to avoid depleting weaker nodes and balance the network

4. Finally we have designed a Proactive Routing Protocol which is adaptive to our Routing Metric FED and simulation results showed better performance than CTP and other routing protocol.

1.9 Organization of the Thesis

This thesis is broken down into following chapters. Chapter 2 provides a literature review which covers routing methods of EH-WSNs. Chapter 3 describes the problem statement and Chapter 4 describes the proposed routing system in detail. Chapter 5 presents experimental analysis which highlights the performance of our proposed routing comparing to other existing approaches. Chapter 6 is the final segment which contains the conclusion of the thesis with the summary and possible future improvements of our proposed approach.

Chapter 2

Literature Review

2.1 Related Work

An efficient routing can greatly improve the performance of any network. Efficient routing metric consists of a Routing Metric and a Routing Protocol. Many research works have done in the field of routing in EH-WSN.

2.2 Routing Metric

2.2.1 Solar Aware Routing

Many research works have been carried out on energy harvesting routing protocols.Voigt et al. [6] first proposed a solar aware routing protocol similar to directed diffusion, which prefers to route data package via solar powered nodes. They introduced one of the first routing metric EH-WSN. For their routing they classified nodes as either harvesting or non harvesting. A harvesting node can gain power from renewable energy and extend its lifetime. On the contrary a non-harvesting node has a limited lifespan which cannot be extended easily. Their routing metric proposed to avoid non-harvesting nodes by selecting harvesting nodes to increase the lifespan of the network. However, the protocol does not consider the residual battery level or the predicted energy harvest. In [22] the solar harvesting nodes will be selected as cluster heads. Cluster algorithm is integrated with the solar energy.

2.2.2 Harvest Rate

As in EH-WSN the main characteristics is to harvest from ambient environment, harvest rate is one of the main issue in routing. Higher harvest rate maximizes the efficiency of routing. In [29] and [30] they incorporate harvest rate with battery energy and showed improved decision in routing. In elects cluster heads based on residue energy and harvest rate.

2.2.3 Cost

Again the role of all nodes are not same in EH-WSN. The data is not all the same and other there are some effects of environment. Routing cost in perspective to many points, energy consumption and current energy should be in consideration. Minimal Total Power Routing Metric (MPTR) in [32] gives a technique where overall energy consumption is minimized. Interestingly when considering lightly loaded path and good link it always tends to yield the same route with minimum hop count metric. It considers per-packet energy consumption which deviate the aim of achieving perpetuality. MBCR in [33] gives a solution by proposing a metric based on remaining energy capacity of the node.The ratio of Remaining Capacity and Full Capacity of battery will give optimum result. An obvious disadvantage is that the selected route may have well featured with small remaining energy. Min-Max Battery Cost Routing(MMBCR) in [34] modified MBCR by minimizing the maximum power required at any node in a network. But it has no guaranty that the MMBCR minimizes the total energy consumed over the path and not clear about the trade-off between individual node and overall system energy optimization. Channel Interference and Noise Minimization is the Key consideration in [38]. Channel Condition is another factor which is noticed and given solution by [35]. Sensor nodes are deployed in huge area. Distance between all nodes are varying very much.It is very common that the distant routes will consume more energy than shortest route. In [37] comes with an idea that considers Euclidean distance and take decision based on that result. Jakobsen et al[11] proposed a new concept 'energy distance' which taken into consideration when determining the route. To be more specific, the spatial distance between any certain sender node and its receiver node is transformed to a weighted distance which is so called the 'energy distance' (the 'weight' here is related to the current energy status of the sender). And the aim of DEHAR is to gure out the route with minimum total energy distance rather than spatial distance in general sense. Their concern is to find and maintain energy optimized routes from any source node to a base station (called the sink or destination node in the following). By energy optimized routes it is meant routes that avoid nodes with too little energy, effectively allowing these nodes to regain their energy level through energy harvesting.

2.2.4 Workload

There can be thousands of nodes in a network. All of the nodes never be equal in terms of importance. Some nodes have more works than others. So, the load of different nodes is an important criteria in consideration of Energy Harvesting WSN. In [38] presented a new consideration of selecting routes that is workload of different nodes. He aligned the workload allocation of different nodes with the energy availability of harvesting nodes. The main goal is to achieve energy neutral operation and maximum performance of the network. Routing protocol based on a distributed Bellman-Ford method that associates a weight representative of a nodes effective energy on each link. Integrate with environmental power constraint [39] considers a metric to maximize the workload.

2.2.5 Residual Energy and Harvest Rate

A new consideration of metric which incorporates residual energy with solar cell is proposed in [40] which presents a dynamic and hierarchical algorithm called MEGA which constructs cluster and elects cluster head based on residue energy and energy harvest rate. Initially, nodes start with a certain amount of energy, and all of them are able to sniffer environment, build and maintain routing table, send or relay packets. Nodes that have relatively higher energy harvesting rate or lower work load will maintain a high energy level. Energy level of nodes will drop after time passes by. For instance, nodes that stay around cluster head are responsible for more packets relay; the nodes that stay in a versatile environment are required to generate and initiate more data, or nodes that stand at edge of the field harvest much less energy.

2.2.6 Residual Energy and Harvest Rate

In [37] comes with a new idea that considers euclidean distance and energy consumption rate as a metric of this protocol.The main objective of this paper is to maximize the lifetime. To obtain this aim this paper tries to optimize the fairness of energy consumption among nodes in the network.

2.2.7 ENR: Energy Neutral Routing [14]

They proposed Energy Neutral Routing (ENR) with a goal to maintain the network in an Energy Neutral state under which a certain performance level can be maintained perpetually. They argued that as energy is being harvested, lifetime of the network is prolonged comparing to the earlier condition. Now, performance within the network can be improved. They proposed a method where for a time slot an energy budget is calculated for each node. During path discovery phase of DD, the node with enough energy budget will allow packets for relay.

2.2.8 WAR: Wastage-Aware Routing [5], [17], [23]

One recent work [5][17] shows that further performance improvement can be achieved by incorporating wastage of energy in route decision consideration. Where wastage energy means, the amount of energy produced from battery overcharge of limited capacity battery, which is suppose to be lost unless used. Such loss of energy due to overcharge on fixed-capacity batteries is referred as wastage of energy.

In WAR the total network energy wastage due to selecting a route Φ_n is the summation of on path wastage of Φ_n and off path wastage of Φ_n. Where off path wastage on node V_i is $e_{w\_off\_i}$,and refers the energy wastage on V_i if not used in route Φ_n. On the other hand $e_{w\_off\_i}$ on path wastage on node V_i refers to wastage of energy even after getting involved in route Φ_n. Equation 2.1 and **??** defines the off path wastage and on path wastage any node V_i in route Φ_n .

$$e_{w\_off\_i} = max(0, e_i + e_{h\_i} - B) \tag{2.1}$$

$$e_{w\_on\_i} = max(0, e_i + e_{h\_i} - e_{c\_i} - B) \tag{2.2}$$

The total network wastage for using a route Φ_n is the summation of on path wastage on Φ_n and off path wastage for not using Φ_n. And their route cost function is the summation of energy consumption due to packet transmission in route Φ_n and the total network energy wastage due to battery overcharge because of using route Φ_n. Equation 2.3 define the cost function of WAR.

$$C(\sigma_n) = \sum_{v_i \epsilon \sigma_n} (e_{c\_i} - e_{w\_on\_i}) + \sum_{v_i \not\epsilon \sigma_n} e_{w\_off\_i} \tag{2.3}$$

The resultant energy of a node on V_i route Φ_n is utilized is ,

$$e_i{}^*(\sigma_n) = \begin{cases} e_i + e_{h\_i} - e_{c\_i} - e_{w\_on\_i} & v_i \,\epsilon\, \sigma_n \\ e_i + e_{h\_i} - e_{w\_off\_i} & v_i \not\epsilon\, \sigma_n \end{cases}$$

To depict the profits of wastage aware routing, following sample network shown in Figure 2.1 can be a good example.

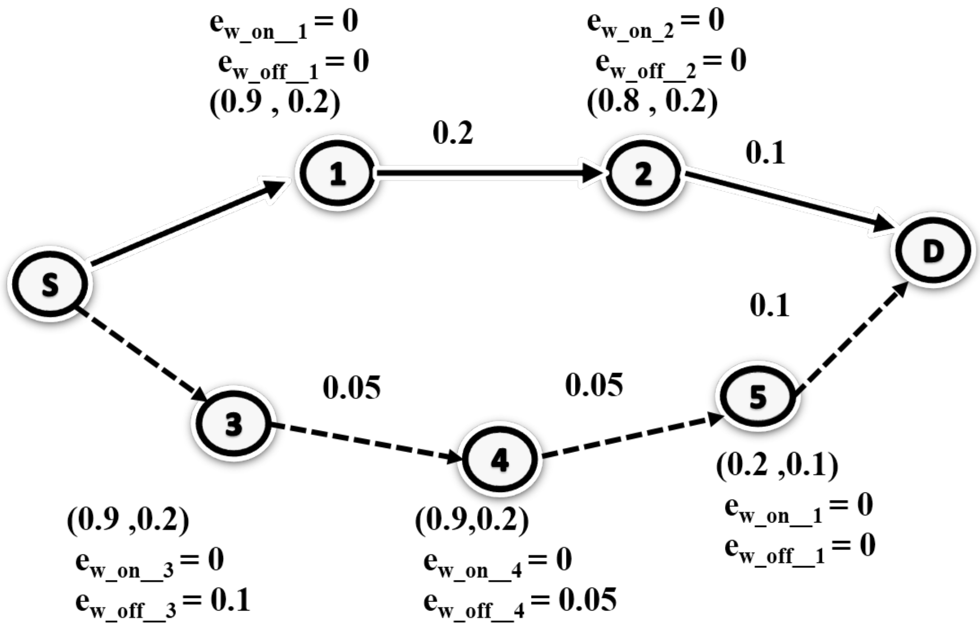

Figure 2.1: Wastage Aware Routing

In the sample network there exists two routes between source node s and destination node d. The route $(s, 1, 2, d)$ and $(s, 3, 4, 5, d)$ are referred as Φ_i and Φ_j respectively. The label V_i (x, y) indicates present battery energy level of x and energy harvesting amount of y in node i.Values along with each links represents the amount of energy consumed in respective links. However, all energy labels are expressed as a fraction of total battery capacity B. If Φ_i is picked as route then the total network energy after route utilization will be 4.5 B and total wastage will be 0.15 B. While if Φ_j is used as route then, maximum total network energy of 4.55 B will be achieved with minimum amount of 0 B being wasted. Though, Φ_i is better than Φ_j in the consideration of energy consumption due to transmission, yet Φ_i is not preferable as it does not result in maximization of network energy. Thus, the consideration of wastage energy in route selection mechanism can leads to maximized total residual network energy.

Ashraf et.al proposed a routing protocol Energy Adaptive Data Delivery in EH-WSN [23] which gave emphasis on minimizing energy wastage and maximum remaining energy by fair distribution of traffic. As routing metric Gina Martinez [5] used energy depletion to minimize wastage but Ashraf considered FED (Fraction of energy Depletion) instead of energy depletion to ensure the fair traffic distribution of traffic into the network. Choosing the path with lowest FED may result in higher cost route to make balance between this he used (PFED) prioritized fraction of Energy Depletion which is the multiplication FED and ETX of that route. ETX expected transmission count relates with channel condition. The route that will give minimum PFED is chosen. This routing is best suitable for Reactive routing protocol but we may not get the desired result in periodic network where huge amount of data exchanged periodically.

$$
\begin{aligned}
PFED_n &= C(\sigma_n) \\
&= \sum_{v_i \epsilon \sigma_n} (e_{fed\_i} \ * \ ETX_{ij}) \\
&= \sum_{v_i \epsilon \sigma_n} (e_{fed\_i}) \ * \ ETX_n
\end{aligned}
$$

2.3 Routing Protocol

2.3.1 Adhoc On Demand Routing Protocol(AODV)[27]

An ad-hoc network is a Reactive routing protocol which is cooperative engagement of a collection of mobile nodes without the required intervention of any centralized access point or existing infrastructure. In AODV the nodes are not lied on active paths neither maintain any routing information nor participate in any periodic routing table exchanges. Further a node does not have to discover and maintain a route to another node until the two need to communicate unless the former node is ordering its services as an intermediate forwarding station to maintain connectivity between two other nodes.

When the local connectivity of the mobile node is of interest each mobile node can become aware of the other nodes in its neighborhood by the use of several techniques including local not (system wide) broadcasts known as hello messages.

The routing tables of the nodes within the neighborhood are organized to optimize response time to local movements and provide quick response time for requests for establishment of new routes The algorithms primary objectives are:

1. To broadcast discovery packets only when necessary
2. To distinguish between local connectivity management neighborhood detection and general topology maintenance
3. To disseminate information about changes in local connectivity to those neighboring mobile nodes that are likely to need the information

AODV uses a broadcast route discovery mechanism [24] as is also used with modifications in the Dynamic Source Routing (DSR)[25] algorithm. Instead of source routing however AODV relies on dynamically establishing route table entries at intermediate nodes This difference pays of in networks with many nodes where a larger overhead is incurred by carrying source routes in each data packet. To maintain the most recent routing information between nodes we borrow the concept of destination sequence numbers from DSDV. Unlike in DSDV however each ad-hoc node maintains a monotonically increasing sequence number counter which is used to supersede stale cached routes The combination of these techniques yields an algorithm that uses bandwidth efficiently by minimizing the network load for control and data traffic is responsive to changes in topology and ensures loop free routing [27].

2.3.2 Dynamic Source Routing(DSR)[26]

The Dynamic Source Routing protocol (DSR) is a simple and efficient routing protocol designed specifically for use in multi-hop wireless ad-hoc networks of mobile nodes. DSR is also a reactive routing protocol. DSR allows the network to be completely self-organizing and self-configuring, without the need for any existing network infrastructure or administration. The protocol is composed of the two mechanisms of Route Discovery and Route Maintenance, which work together to allow nodes to discover and maintain source routes to arbitrary destinations in the ad hoc network. The DSR protocol allows nodes to dynamically discover a source route across multiple network hops to any destination in the ad hoc network. Each data packet sent then carries in its header the complete, ordered list of nodes through which the packet must pass, allowing packet routing to be trivially loop-free and avoiding the need for up-to-date routing information in the intermediate nodes through which the packet is forwarded.

The DSR protocol is composed of two mechanisms that work together to allow the discovery and maintenance of source routes in the ad hoc network.

- Route Discovery is the mechanism by which a node S wishing to send a packet to a destination node D obtains a source route to D. Route Discovery is used only when S attempts to send a packet to D and does not already know a route to D.
- Route Maintenance is the mechanism by which node S is able to detect, while using a source route to D, if the network topology has changed such that it can no longer use its route to D because a link along the route no longer works. When Route Maintenance indicates a source route is broken, S can attempt to use any other route it happens to know to D, or can invoke Route Discovery again to find a new route. Route Maintenance is used only when S is actually sending packets to D.

2.3.3 Destination-Sequened Distance Vector (DSDV) Protocol

The Destination-Sequenced Distance Vector (DSDV) protocol is a table-driven routing protocol based on the improved version of classical Bellman-Ford routing algorithm. DSDV is based on the Routing Information Protocol (RIP). With RIP, a node holds a routing table containing all the possible destinations within the network and the number of hops to each destination. DSDV is also based on distance vector routing and thus uses bidirectional links. A limitation of DSDV is that it provides only one route for a source/destination pair. DSDV Packet Process Algorithm:

1. If the new address has a higher sequence number, the node chooses the route with the higher sequence number and discards the old sequence number.
2. If the incoming sequence number is identical to the one belonging to the existing route, a route with the least cost is chosen.
3. All the metrics chosen from the new routing information are incremented.
4. This process continues until all the nodes are updated. If there are duplicate updated packets, the node considers keeping the one with the least-cost metric and discards the rest.

Routing Table for Node 2

Destination	Next Hop	Metric	Dest. Seq. No.
1	1	1	123
2	0	0	516
3	3	1	212
4	4	1	168
5	4	2	372
8	1	INF	432

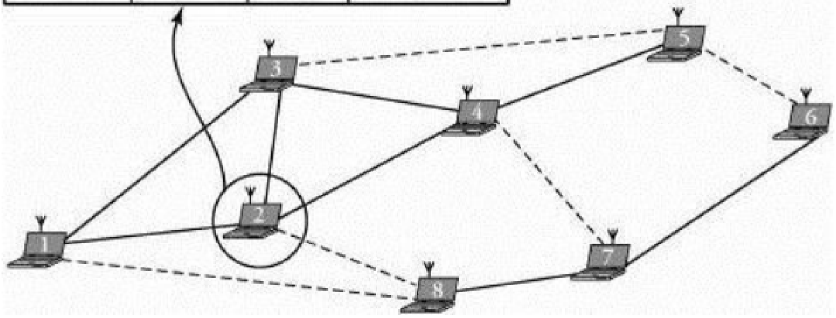

FIGURE 2.2: DSDV Routing

2.3.4 Collection Tree Protocol(CTP)[28]

CTP is a tree-based collection protocol. Some number of nodes in a network advertise themselves as tree roots. Nodes form a set of routing trees to these roots. CTP is address-free in that a node does not send a packet to a particular root; instead, it implicitly chooses a root by choosing a next hop. Nodes generate routes to roots using a routing gradient. The CTP protocol assumes that the data link layer provides four things:

1. Provides an efficient local broadcast address.
2. Provides synchronous acknowledgments for uni-cast packets.
3. Provides a protocol dispatch field to support multiple higher-level protocols.
4. This process continues until all the nodes are updated. If there are duplicate updated packets, the node considers keeping the one with the least-cost metric and discards the rest.

CTP assumes that it has link quality estimates of some number of nearby neighbors. These provide an estimate of the number of transmissions it takes for the node to send a uni-cast packet whose acknowledgment is successfully received. CTP is designed for relatively low traffic rates such that there is enough space in the channel to transmit and receive routing frames even when the network is forwarding collection data frames. Bandwidth-limited systems or high data rate applications might benefit from a different protocol, which can, for example, pack multiple small frames into a single data-link packet or employ rate control mechanisms.

CTP uses expected transmissions (ETX) as its routing gradient. A root has an ETX of 0. The ETX of a node is the ETX of its parent plus the ETX of its link to its parent. This additive measure assumes that nodes use link-level re transmissions. Given a choice of valid routes, CTP SHOULD choose the one with the lowest ETX value. CTP represents ETX values as 16-bit decimal fixed-point real numbers with a precision of tenths. An ETX value of 45, for example, represents an ETX of 4.5, while an ETX value of 10 represents an ETX of 1.

Chapter 3

Problem Statement and Motivation

3.1 Introduction

This chapter discusses the problem statement and motivation of my thesis work in a detailed manner. Our assumed network and system model description is included at the very beginning of this chapter.

3.2 Network Model and Assumption

We consider an energy harvesting sensor networks with flat, multi-hop tree like topology, where N sensing nodes are deployed in outdoor terrain. The network can be described by a undirected graph *G(V,E)* where V is the set of vertices representing the sensor nodes and E is the set of edges representing links. Each node V_i can take the role of a source or forwarder at any time. There exists an edge $e_{ij} \epsilon E$ between V_i and V_j when they are within each others radio transmission range. We assume the maximum radio transmission range is same for all sensor nodes.

We consider a single sink in the network placed at anywhere within the terrain. All the sensor nodes are static and homogeneous i.g. all sensor nodes possess the equal processing power and equal sensing and transmission range. All the sensor nodes follow the standard IEEE 802.15.4 MAC Protocol for medium access. However,we are also considering the presence of no misbehaving sensor nodes in network. Each sensor node V_i is equipped with a solar photovoltaic (PV)

Table 3.1: List of Notation

Property	Notation
Total Battery Capacity	B
Current Battery Level on node V_i	e_i
Prediction Horizon, a future period to predict harvest and consumption	Δt
Expected Energy Harvest on Node V_i over Δt	e_{h_i}
Expected Energy Consumption on Node V_i for using a particular Link over Δt for data delivery	e_{c_i}

modules, which have equal capabilities of generating and suppling solar electricity. However, energy harvesting rate of each nodes V_i is a variable entity and is a function of sensor's ecological position and its surrounding environmental impact.

We consider a periodic network where data generation rate of each sensing nodes is assumed to be equal. Each nodes generates x data packets in each data generation period t . Sink node can gather explicit knowledge regarding each sensor's mutual RF connectivity and their respective energy status during route. Table 3.1 contains a list of notation those will be frequently used in our work.

3.2.1 Prediction Horizon

The prediction horizon, a future period for which prediction on harvest and consumption is considered, has significant role in affecting network performance. Too frequent prediction may lead unnecessary overhead and energy cost. On the other hand estimation for very long period may results in wrong decision and performance deterioration. Thus an appropriate prediction should be set.

However,Energy reduction rate in a sensing nodes varies depending of traffic load carried by it. On the other hand energy harvest rate in nodes depends on local weather condition, local region impact etc. Moreover stochastic nature of availability of harvest energy has made it more impractical to set a constant value for prediction horizon T. Thus T is set as a variable in our case and is adaptively decided by sink and announced it in network .

3.3 Problem Statement and Motivation

The performance of EH-WSN largely depends on the perpetual operation of the sensor networks. Temporary death of certain nodes results discontinuity in communication process and deteriorates overall network performance. Therefore, the ultimate objective of communication protocols on EH-WSNs includes the assurance of *perpetual network operation.*However, to ensure *perpetual network operation* following two goals are promising requisites .

1. Maximization of Network Remaining Energy
2. Balancing between maximum remaining energy and minimum energy level

Since routing strategy significantly influences the energy state in network, thus this becomes a critical issue in EH-WSNs which need to be handled intellectually. Route selection strategy takes substantial role in minimizing energy consumption as well as balancing energy depletion in EH-WSNs.

Existing route selection schemes in EH-WSNs consider a set of properties associated with energy harvesting nodes and networks. Among them

- Node residual energy
- Predicted harvest energy
- Estimated energy consumption
- Channel condition
- Weak Node Condition
- Rapid Degradation of Good Path

are mentionable. Undoubtedly, for the assurance of perpetual operation all of these components carry significant importance in directing any route.

Routing metric ED ensures the minimization of energy cost as well as maximization of network remaining energy. However, only minimization of energy cost doesn't always ensure the long term network connectivity. Always using the path that causes minimum energy depletion may not be optimal from the point of view of network lifetime and long term network connectivity. Hence, consideration on balanced energy depletion is also crucial to ensure perpetual network operation. Absence of this consideration in route selection strategy can results in limited network life time especially in large and network where high number of data traffic is forwarded by the nodes closer to sink nodes. And such consequence can take place in a scenario where leaf nodes in the network are still experiencing excess of harvest energy as well as wastage energy. Since nodes closer to sink nodes usually have higher energy consumption than whatever they harvest from limited capacity harvester. On the other hand, leaf nodes or closer to leaf nodes usually have less energy consumption since they don't need to forward others data traffic. Therefore, maximization of minimum energy level in network is also important issue which we have to include in our route selection consideration to ensure perpetual network operation .

Therefore, the ratio of energy depletion whatever they contribute because of getting involved in a route σ_n should be justified. Proportional thinking of energy depletion can be a effective way to handle this issue. The representation of energy depletion as a fraction of remaining energy can provide a perfect weight of the contribution of depletion. we refer this term as Fraction of Energy Depletion (FED), which is the proportion of energy depletion e_{ed} and remaining energy before getting included in route, e_i^*. Where

$$e_i^* = e_i + e_{h\_i} - max(0, e_i + e_{h\_i} - B)$$

Hence, we define the Fraction of Energy Depletion (FED) on node i as $e_{fed\_i} = \frac{e_{ed\_i}}{e_i^*}$
Thus the Fraction of Energy Depletion FED on *node i* , e_{ed} depict the

1. Proportion of energy contribution in the route
2. Current energy strength of the sensor nodes

As a elucidation, the following example in figure 3.1 is enclosed. Though the energy depletion, e_{ed} in both *node i* and *node j* shown in figure 3.1 is 0.1 B, the proportion of their energy contribution doesn't carries equal weight. *node i* will contribute its (0.1/0.9)B = 0.11 B = 11 % of remaining energy and *node j* (0.1/0.5)B = 0.20 B = 20% of its remaining energy. Thus, between them, the exclusion of *node j* from any route will be encouraged than *node i*.

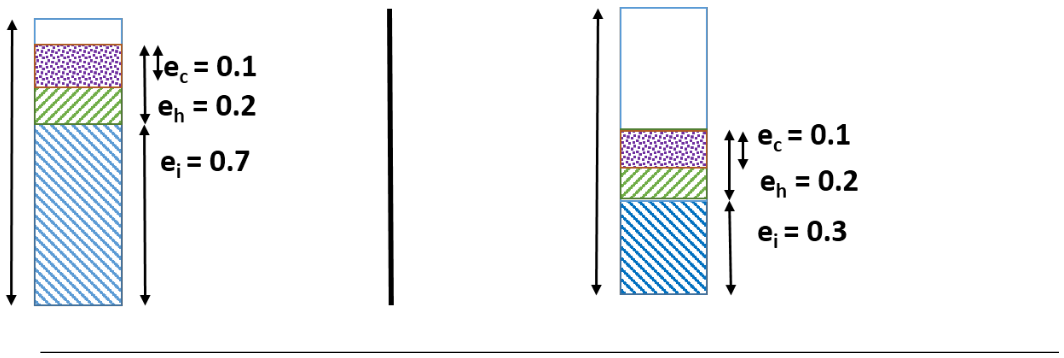

FIGURE 3.1: Fraction of Energy Depletion on node i (a) and node j (b)

Thus, satisfaction of following goals will be adequate to assure perpetual network operation in EH-WSNs.

1. Minimization of Energy Consumption
2. Maximization of Residual Energy
3. Acquiring a Balanced Position between
   (a) Minimization of Energy Consumption and Maximization of Residual Energy
4. Avoiding degradation of best path.

in network. Thus, this thesis work focus on designing an appropriate routing for EH-WSN with the objective of

1. Modification of PFED metric for heterogeneous network
2. Avoid the Rapid degradation of best path
3. A Proactive Routing Protocol adaptive with PFED metric.

Chapter 4

Proposed Method

4.1 Introduction

This chapter discusses the proposed scheme of my thesis work in a detailed manner. The proposed scheme has been designed to address the problems stated earlier so that an effective route selection scheme can be achieved.

4.2 Proposed Routing

Most appropriate use of harvest energy is the ultimate consideration while selecting the routes. Minimization of wastage energy is another consideration in route selection strategy. Total network energy wastage minimization actually leads to maximized network remaining energy. Calculation procedure of total network wastage in [5], [17] results in huge overhead and is impractical in large network.However, we handle this issue in different but simple way. From [23] to meet the balanced energy depletion condition they define their final routing metric *Prioritized Fraction of Energy Depletion (PFED)* where the cost function for any route σ_n is given by following equation

$$
\begin{aligned}
PFED_n &= C(\sigma_n) \\
&= \sum_{v_i \epsilon \sigma_n} (e_{fed\_i} \, * \, ETX_{ij}) \\
&= \sum_{v_i \epsilon \sigma_n} (e_{fed\_i}) \, * \, ETX_n
\end{aligned}
$$

We use this Routing Metric with few updates adaptive with our routing protocol. Sink keeps track of updated energy state of all nodes in its local table. Since multiple route exists for any single source , sink node after getting multiple copy of RREQ packet having same route request id. Each of them contains on path energy state for multiple routes from same source. Sink calculates cost for each routes by utilizing per hop information available in RREQ headers. Sink calculate of e_{c_i} from x_i, etx_{i_j} and e_z. Where, e_z refers to energy depletion for per unit of data transmission, which is a provided by our battery depletion profile. Our battery depletion profile is discussed in chapter 5. CTP and other route engine at sink then choose a rote σ_n^* from a set of routes from same sink σ which holds the minimum cost value. Once a route is selected, corresponding nodes energy information is updated in sink local table. Confirmation of a route is than informed to corresponding nodes through route reply packet. The sink broadcasts route flood which contains PFED, the nodes receiving the route flood increments the PFED with it's own FED and broadcast the route flood. Upon receiving route flood each node prepare a prioritized list of it's upstream neighbors. Then every sending node will pick a random number using the following formula. It will take the average of PFED of neighbors when neighbors PFED will be within certain range.

$$p = \sum_{i=1}^{j} n_i \,.PFED\ /j;$$

$n_i = Node\ in\ priority\ list$ With PFED in range

Then a random number is generated, PRAND = 0-p. According to this value of random no. the parent will be selected among the neighbors. In this process the neighbor with best metric will be selected most of the times and second best or third best will be selected a few times. Every node will select it's downstream neighbor and eventually reach the sink in this way. By using this probabilistic selection Rapid degradation of best path is overcome here.

4.2.1 Implementation of Metrics on Different Protocols

We apply routing metrics ED, FED and PFED on DSR(Dynamic Source Routing), CTP(Collection Tree Protocol), AODV(Adhoc On Demand Routing Protocol) and in our Proposed protocol to performance evaluation.

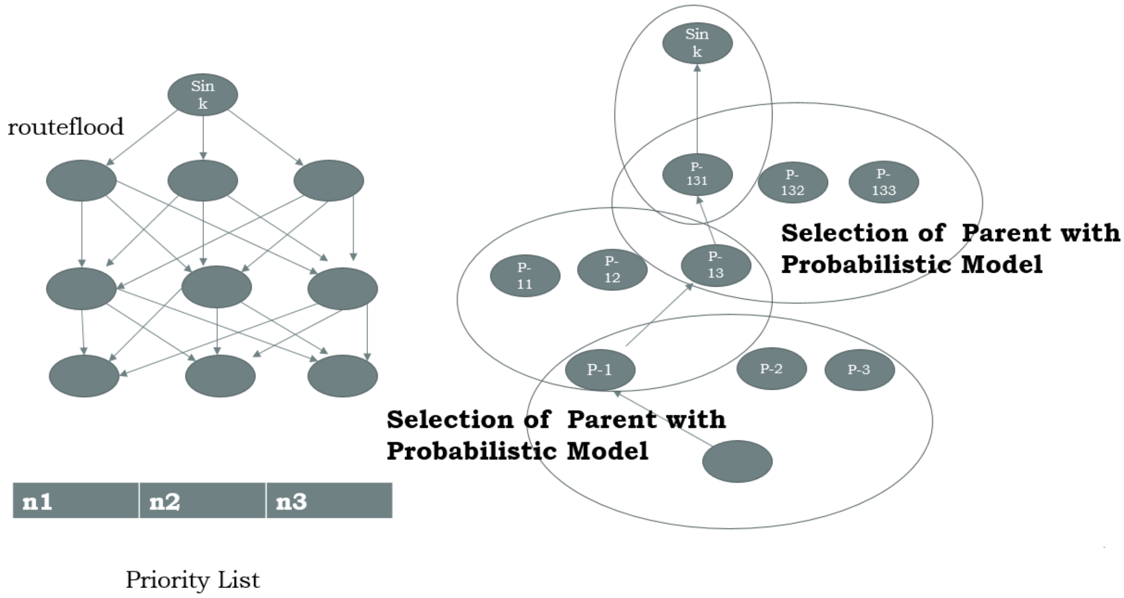

Figure 4.1: Routing Process

4.2.2 Our Contribution

We did performance evaluation of On-Demand Routing Protocols in Real Test-Bed environment(TelosB-Mote). Then PFED metric is taken into percentage to use in heterogeneous network. To avoid rapid degradation of best path we put two threshold energy thus weaker nodes are excluded and balance the network. An adaptive routing protocol is designed for periodic environment in EH-WSN to achieve perpetual network lifetime. Finally we measured the Performance evaluation with different metrics in CTP vs Our Proposed Protocol.

Chapter 5

Simulation Result and Performance Analysis

5.1 Introduction

This chapter discusses simulation parameters, setup and performance analysis of this thesis work in a detailed manner.

5.2 Simulation Parameters

A simulation is conducted in order to evaluate the performance of the proposed routing Protocol in comparison to the Collection Tree Protocol (CTP). Five TelosB sensor nodes have been used for this simulation and the nodes are arranged in a tree like topology .A sink node is placed as the root and four other nodes are placed in such a way that the leaf nodes can send data to the sink via the intermediate nodes hence they are two hops away from the sink. The sink is connected with unlimited power and always ready receive data. Figure: 1 shows the simulation environment:

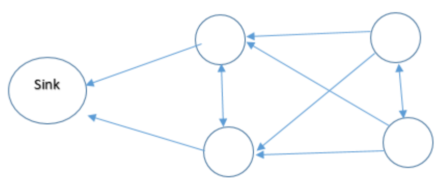

FIGURE 5.1: Network Topology

Table 5.1: Energy Depletion Rate

Battery Voltage	Reduced Amount for 1 byte of Transmission(Voltage)	Percentage of total Effective Battery Voltage
100%-50%	0.000104167 unit of ADC Count	4.16667E-06%
50%-10%	0.000091125 unit of ADC Count	4.55625E-06%
10%-1%	0.0125 unit of ADC Count	0.0005%

5.2.1 Battery Depletion Profile

We did TestBed implementation by Telosb motes in TinyOS Platform to understand the actual battery depletion nature in different workload.Where, Telos is an ultra low power wireless module for use in sensor networks, monitoring applications, and rapid application prototyping. Telos leverages industry standards like USB and IEEE 802.15.4 to inter-operate seamlessly with other devices.

Figure 5.2: Telosb Mote used in Testbed implementation

We generate data traffic at different rate and did extensive analysis on their battery depletion profile . Continuous observation on their battery depletion over time helps us point out their average battery depletion for per unit of data transfer.Table 5.1 depict that outcome.

While two Alkaline AA battery each of 1.5 V is attached in telosb mote , Its total internal voltage becomes 3.0 V. However, minimum voltage level required for TelosB mote to be in functionality is 1.5 V resulting 1.5 V effective voltage to be used. Figure 5.2 shows the battery depletion nature of telosb mote while carrying out variable traffic loads.

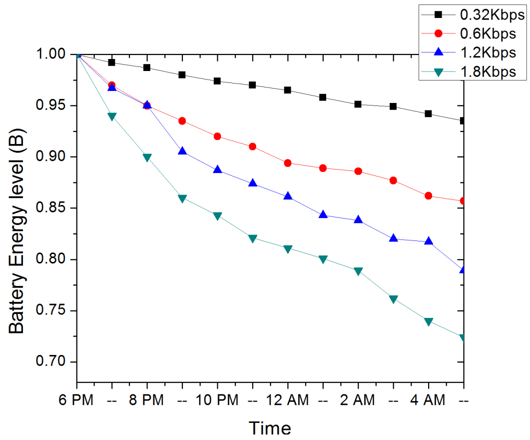

FIGURE 5.3: Battery Depletion Nature of Telosb mote at different data rate

5.3 Simulation Setup

- We have used TelosB Mote in real test bed for simulation.
- We simulate considering the outdoor environment.

In all simulations, a total of N nodes are placed within a fixed area of 500m 500m. The transmission range of all nodes is 30m. Within a connection stream, the source originates packets in a constant bit rate (CBR) manner at a specified data rate p. The source continues to produce packets during the entire connection stream duration Tcs.

We performed simulation on the proposed metric ED, FED PFED along with WAR by varying harvest profile and traffic load on the following configuration:

- **Structure of network :**Tree like
- **Mobility Model :**Constant
- **Initial Battery Capacity :**4045 ADC or 2.9 V
- **Transmission Range :**50 meter
- **Packet size :**128 bytes
- **Simulation Are :**120*150 meter
- **No. of Nodes :**5
- **Transmission Interval :**1 sec
- **Simulation Time :**36000 sec

5.4 Simulation Results

At first we simulated the CTP protocol in different metrics: FED, PFED and ETX. In simulation we measured the average Voltage, Minimum Voltage and balancing of voltage of the nodes of the network

5.5 Performance Evaluation

5.5.1 Performance of PFED, FED, ETX Metric on CTP

We measured the average voltage of the nodes for the above mentioned topology of network on CTP using PFED, FED, and ETX metric. The metric that gives the higher average voltage is better. Our simulation result shows that both PFED & FED gives higher average voltage where ETX metric results in lowest average Voltage. So in terms of average voltage of the network PFED & FED metric is better. The following figure shows the simulation results:

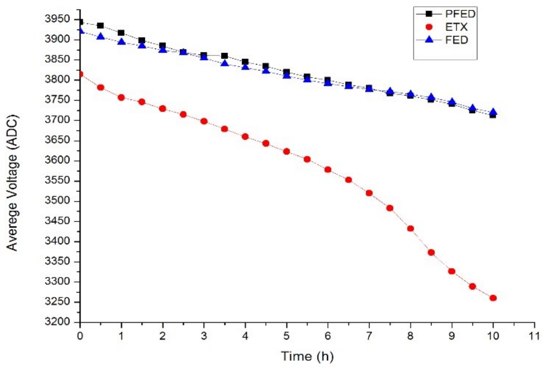

FIGURE 5.4: Average Voltage in ETX,FED & PFED

We measured the minimum voltage of the nodes of the network. The goal of our routing is to maximize the minimum Voltage of the nodes of the network. We measured the minimum voltage of the nodes using PFED, FED & ETX metric on CTP. Our simulation result shows that FED metric works best in maximizing the minimum voltage whereas ETX gives the worst result. The figure shows the minimum voltage of network in different metrics:

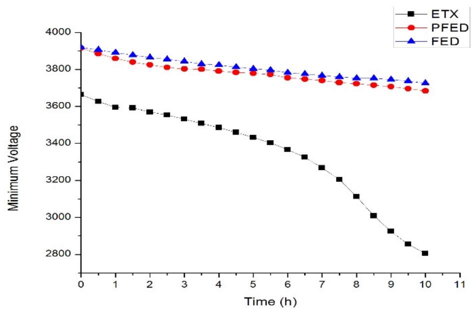

Figure 5.5: Minimum Voltage in ETX,FED & PFED

Another key concern of our routing mechanism is to balance the load among the nodes of the network so that no nodes energy depletes drastically. In this process to balance the load we often choose the bad path. Our simulation results shows that PFED does the load balancing better than any other metric. Figure shows the load balancing on CTP using three different metric:

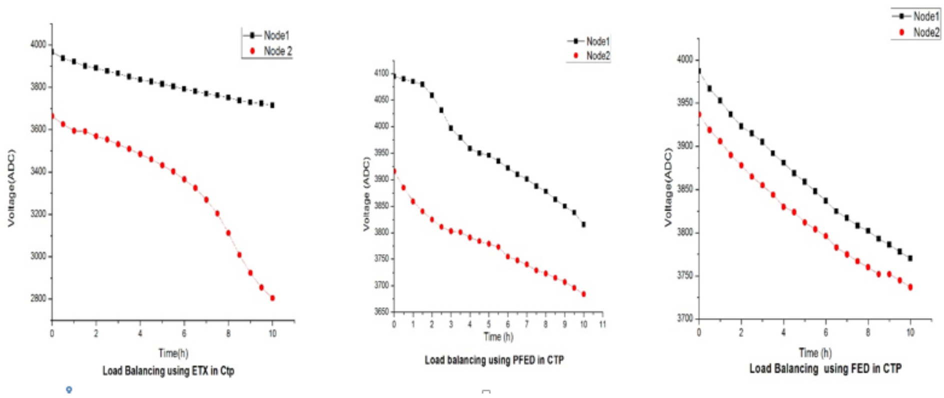

Figure 5.6: Load Balancing in CTP using ETX, FED & PFED

Analyzing the simulation results we find that PFED metric gives the best result and we took PFED as the routing Metric of our routing protocol.

5.5.2 CTP vs Proposed Protocol on Metric PFED

PFED gives the best result as metric and in this part we measured the performance of CTP and Our proposed Protocol on metric PFED.

We measured the average voltage of the nodes of the network using our proposed protocol and CTP on Metric PFED. Simulation results show that our proposed protocol outputs higher average Voltage after 10 hours of simulation then the Collection Tree protocol.

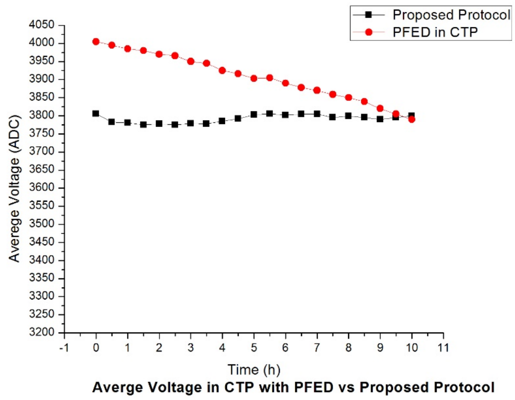

Figure 5.7: Average Voltage in CTP with PFED vs Proposed Protocol

We measured the minimum voltage of the nodes of the network using our protocol and CTP on metric PFED. Though in CTP initially the average voltage was higher over the simulation time the average voltage of our protocol becomes higher and out performs CTP. Figure shows the simulation result:

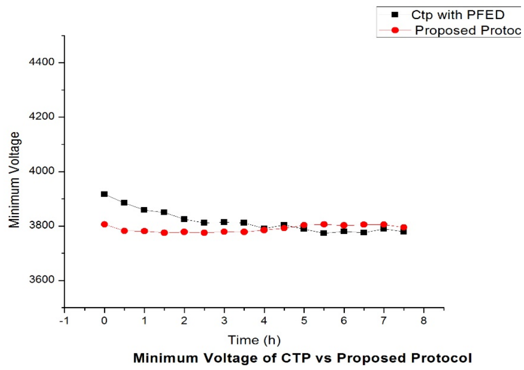

Figure 5.8: Minimum Voltage in CTP with PFED vs Proposed Protocol

We measured the voltage of two intermediate nodes to measure the load balancing and simulation result shows the proposed protocol works better than the Collection tree protocol (CTP).

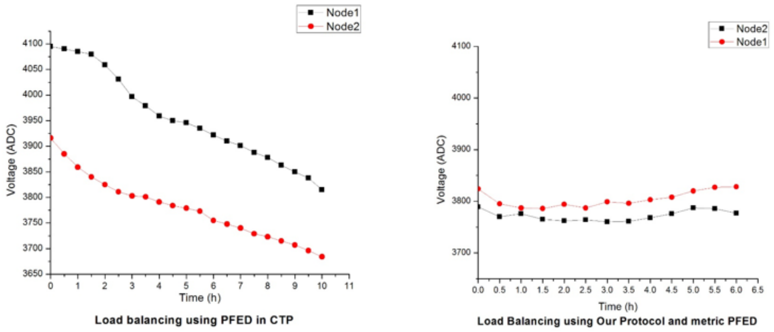

FIGURE 5.9: Load Balancing in CTP vs Proposed Protocol with PFED Metric

The simulation results shows that our protocol outperforms the CTP maintaining higher average voltage, minimum voltage and balanced voltage level of the sensor nodes.

5.5.3 Perpetual Network Lifetime

The above mentioned simulation results shows that our protocol performs better than CTP in terms of energy in 10 hour time slot where harvest rate was the same in 10 hours time-frame. As the networked survived 10 hours without much depletion of energy we can say that given enough solar energy the network will be able to achieve perpetual life time. So we can say that our Routing mechanism along with the proposed metric and protocol ensure perpetual network lifetime of energy harvesting sensor nodes.

Chapter 6

Conclusion

6.1 Summary of Contributions

We did performance evaluation of On-Demand Routing Protocols in Real Test-Bed environment(TelosB-Mote). Then PFED metric is taken into percentage to use in heterogeneous network. To avoid rapid degradation of best path we put two threshold energy thus weaker nodes are excluded and balance the network. An adaptive routing protocol is designed for periodic environment in EH-WSN to achieve perpetual network lifetime

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