MASTER OF SCIENCE IN COMPUTER SCIENCE
AND ENGINEERING

Energy-Adaptive Data Delivery in Energy-Harvesting Wireless Sensor Networks

by

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Abstract

Renewable energy like solar radiation can be employed for extending the lifespan of a wireless sensor network (WSN) node. Such systems have made it feasible to manage the energy constrain suffered by traditional Wireless Sensor Networks. Instead of only maximizing the network lifetime with a finite amount of energy as in battery-powered network, objective of EH-WSN networking protocols turns into assurance of perpetual network operation. Significant role of route selection strategy in assurance of perpetual network operation in EH-WSNs has inspired us to design a set of efficient routing metrics 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 metric called Energy Depletion (ED) minimizes the wastage of energy in network with minimum overhead and maximizes the total network remaining energy. Secondly, proposed metric named Fraction of Energy Depletion (FED) eliminates the unbalanced energy depletion problem from network . Finally our routing metric named Prioritized FED (PFED) achieves both benefits proportionally by doing a perfect trade off between these two goals.

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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

A wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental conditions is usually known as wireless sensor network. 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.

Although the battery technology has come a long way since its birth, it is hardly capable of keeping up with ever increasing applications and energy demands of WSN. For this reason, researchers and techno-giant companies were seeking proficient systems able to extract necessary energy from greener sources. However, with the emergence of energy harvesting techniques in recent years, 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

With the emergence of energy harvesting techniques, wireless sensor nodes can be equipped with energy harvesting devices so that additional energy can be harvested from the ambient environment. 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 system architecture of a wireless sensor node includes the following components:

- Energy harvester(s): which convert external ambient or human-generated energy to usable power
- Power management module: it collects energy from harvester and uses it by storing or delivering to other components for immediate usage.
- Energy storage unit: it stores the harvested energy for future usage. For storing, super ca-pacitors can be used. They give very large storage within their small size. If harvested en-ergy is greater than the immediate usage, it stores the energy for future when harvesting will be less. Another good option is rechargeable battery.
- Micro controller

- Radio transceiver: it transmits and receive information
- A/D converter: it digitize the analog signal generated by sensors and provide it to micro controller for further processing.
- Memory: it stores sensed information, application-related data and code.

1.2.4 Energy Harvesting Wireless Sensor Network

EH-WSN is a wireless network consist of individual nodes which are able to sense the environment, perform wireless communication and also capable of extracting energy from multiple ambient sources and convert them into usable electrical power. 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.

1.2.5 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.*However, to ensure *perpetual network operation* following two goals are promising requisites .

1. Maximization of Network Remaining Energy
2. Maximization of Minimum Energy Levels in Network

Since route selection 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. Hence, harvest aware route selection strategy can take prominent role in assurance of perpetual network operation in EH-WSNs.

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. Maximizing the Minimum Energy Level in network

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 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

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. However, very few of previous researches considered this issue in route selection strategy.

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.

However, dependency of route cost calculation on remaining routes information has made it a complex mechanism which results in huge overhead. Moreover, requirements of per node information gathering for all off path nodes is mostly impractical specially in case of large network.

Moreover, maximizing the network remaining energy does not always ensure perpetual network operation. Always using the lowest energy path may not be optimal from the point of view of network lifetime. Since,overlooking the critical nodes during route selection may cause overload on certain weak nodes. This scenario is very usual in case of nodes closer to sink nodes in a large network with high data rate. Hence, maximizing the minimum energy level in network is of equal importance.

However,minimization of energy consumption and maximization of minimum energy level in network may be two contradicting goals in some cases. Thus a trade of is essential to get the both benefit proportionally.

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

1. Minimization of Total Network Energy Wastage involving Minimum Overhead.
2. Minimization of Energy Consumption in Network
3. Maximization of Minimum Energy Level in Network
4. Acquiring a Balanced Position between
    (a) Minimization of Energy Consumption and Maximization of Minimum Energy Levels

1.7 Thesis Objective

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

1. Minimizing the Wastage Energy in Network
2. Minimizing the Energy Consumption in Network.

3. Maximizing the Minimum Energy Levels in network and thus ensuing Balanced Energy Depletion
4. Acquiring a Balanced Position between
    (a) Minimization of Energy Consumption and Maximization of Minimum Energy Levels
5. Assurance of above goals involving minimum overhead.

1.8 Thesis Contribution

The primary Contributions of this thesis are stated below:

1. We have proposed a robust routing metric called Energy Depletion (ED) which ensure the maximum feasible utilization of wastage energy and minimum energy consumption in network. Thus it keeps the total network remaining energy in maximum level. Routing metric ED gives preference to routes which result in minimum energy depletion. However, our routing metric ED does not have any dependency on remaining route information and requires no per node information gathering. With minimum overhead routing metric ED is possible to implement in state of the art EH-WSNs routing protocols.

2. We have also designed another routing metric cited as Fraction of Energy Depletion (FED) to assure the energy balance in network. It maximize the minimum energy level and prevents potential early death of weak nodes in network. Routing metric FED gives preference to routes which result in minimum fraction of energy depletion with respect to their remaining energy.

3. Finally the routing metric named Prioritized FED (PFED) is proposed to get a balanced route decision which will do a perfect trade off between above to goals. Proposed routing metric Extended Fraction of Energy Depletion (PFED) assure the balanced position between minimization of energy consumption and maximization of minimum energy levels . Routing metric PFED consider both issues and formulate a combined entity which reflects the dominating entity between these two. Thus PFED does a balanced trade off between Minimization of Energy Consumption and Maximization of Minimum Energy Levels

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 metric in detail. Chapter 5 presents experimental analysis which highlights the performance of our proposed metric 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 metric can greatly improve the performance of any network. For EH-WSNs, a series of routing metrics were proposed to achieve EH-WSNs requirements. In this chapter, few of those are discussed.

2.1.1 Solar Aware Routing [6]

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.

2.1.2 Energy Replenishment Rate Aware Routing [7]

They proposed a routing protocol which incorporated energy replenishment rate into the cost metric when computing routes. They argued that all the harvesting nodes are not same. Different nodes may have different harvesting opportunity. In a distributed application, the same end-user performance may be achieved using different workload allocations, and resultant energy consumptions at multiple nodes. In this case, it is important to align the workload allocation with the energy availability at the harvesting nodes.

2.1.3 GEBRES: Geographic Energy Aware Blacklisting Routing With Energy Supply[8]

They proposed Geographic Energy Aware Blacklisting Routing With Energy Supply (GEBRES) a protocol which makes routing decision locally by jointly taking into account multiple factors the realistic wireless channel condition, packets advancement to the destination, the energy availability on the node with environmental energy supply. Their primary concern is to increase the minimum level of residual energy on the nodes. As their metric consider some important factors the performance is better than the earlier versions, but it introduces some overhead. For their metric it is required to know the geographical location of other nodes, which may not be available.

2.1.4 E-WME: Energy-opportunistic Weighted Minimum Energy [9]

Lin et al. presented the Energy-opportunistic Weighted Minimum Energy (E-WME) [9] routing protocol which assigns each energy harvesting node with a cost that is related to the energy harvesting rate and then calculate the shortest path according to each node's cost.

2.1.5 R-MPRT: Randomized Minimum Path Recovery Time [10]

The Randomized Minimum Path Recovery Time (R-MPRT) routing protocol [10] proposed by Lattanzi et al. assigns to each edge with a cost related to the energy required to transmit a packet and the energy harvesting rate.

2.1.6 DEHAR: Distributed Energy Harvesting Aware Routing [11]

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 figure 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.

2.1.7 AR-MPRT[12]

Hasenfratz et al. compared in [12] the E-WME[9] and R-MPRT[10] protocols and found that if we calculate the cost in R-MPRT with respect to the available energy instead of the energy harvesting rate, its performance will be better than that of E-WME.

2.1.8 ESCFR: Exponential and Sine Cost Function based Route [13]

In their work, sensors with higher remaining energy is given higher priority over remaining sensor in route selection procedure. Two energy aware cost based routing algorithms named Exponential and Sine Cost Function based Route (ESCFR) and Double Cost Function based Route (DCFR) have been proposed in this paper. For ESCFR, its cost function can map small changes in nodal remaining energy to large changes in the function value. For DCFR, its cost function takes into consideration the end-to-end energy consumption, nodal remaining energy, resulting in a more balanced and efficient energy usage among nodes.

However,wasted energy due to battery overcharge was not considered and maximization of network remaining energy was not achieved.

2.1.9 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.

2.1.10 WAR: Wastage-Aware Routing [5], [17]

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

Minimization of the cost associated with the energy consumption due to packet transmission and the total network energy wastage due to battery overcharge were two components of their proposed routing metric, named wastage aware routing metric. With the prime goal of maximizing total network resulting energy, [5] 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 leads to maximized total residual network 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 2.2 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.

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

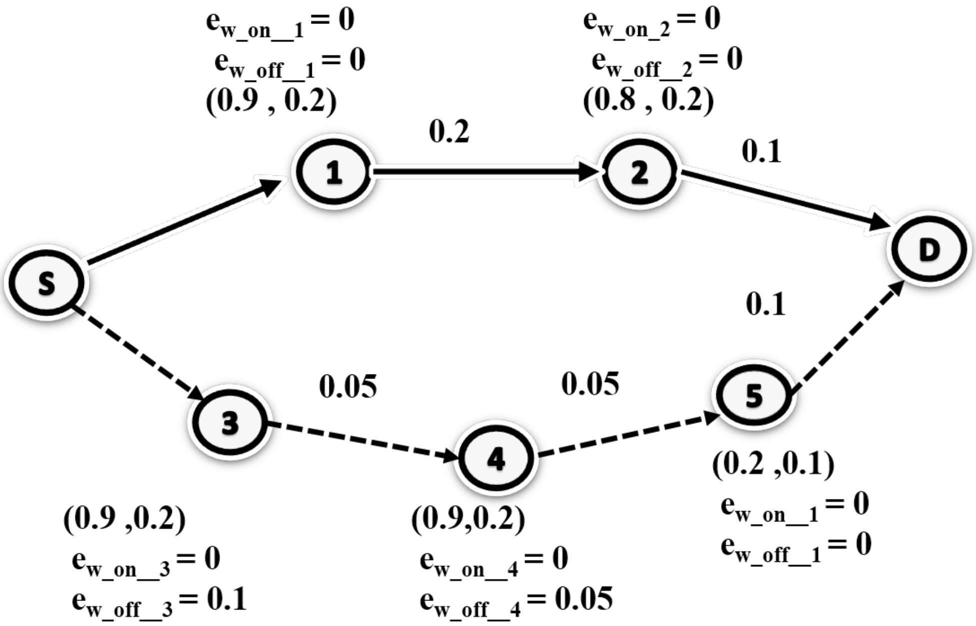

Figure 2.1: Wastage Aware Routing

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.

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) 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

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}

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 nodes. 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. Maximization of Minimum Energy Levels

Since route selection 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. Hence, energy aware route selection strategy is essential to take the prominent role in assurance of perpetual network operation in EH-WSNs. However, for the satisfaction of certain energy objective of EH-WSN, its routing metric should be aimed at

1. Minimizing the Energy Consumption in Networks
2. Maximizing the Minimum Energy Level in Networks

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

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

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. However, very few of previous researches considered this issue in route selection strategy.

Let B the maximum battery capacity and Δt the prediction horizon, a future period to predict harvest amount and consumption due to transmission. The current residual battery level in node V_i is expressed as e_i and e_{h_i} as the estimated harvested energy over Δt. If estimated energy consumption due to be used in route σ_n over Δt is e_{c_i} them, e_i^* represents the resultant energy which is the estimate residual battery after Δt. Thus the wastage amount after Δt node V_i can be expressed by equation 3.1. Since this wastage is because of not using node V_i in route σ_n over Δt, thus this wastage is cited as off path wastage $e_{w\_off\_i}$.

$$e_{w\_off\_i} = max(0, e_i + e_{h\_i} - B) \tag{3.1}$$

However, if route σ_n utilized over Δt then wastage on node V_i is called on path wastage $e_{w\_on\_i}$ and calculated by equation

$$e_{w\_on\_i} = max(0, e_i + e_{h\_i} - e_{c\_i} - B) \tag{3.2}$$

Figure 3.1 and 3.2 clarify the overall concept of energy wastage. Node in figure 3.1 will have 0.1 B amount of wastage if not being used in route. However, it will

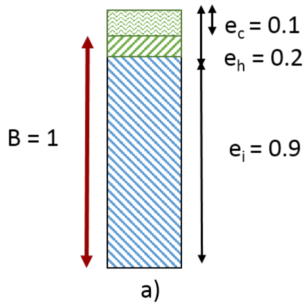

FIGURE 3.1: Energy wastage due to overcharge of battery

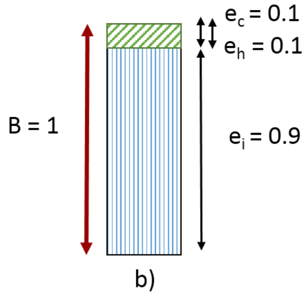

FIGURE 3.2: Energy wastage due to overcharge of battery

have no wastage of energy if get included in route which consumes 0.1 B energy. Node in figure 3.2 will have zero energy wastage in both cases.

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 were two components of their proposed routing metric, named wastage aware routing metric. With the prime goal of maximizing total network resulting energy, [5], [17] choose a route $\sigma_n \epsilon \Phi$ 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.

To depict their approach to maximize the total residual network energy, following sample network can be a good example.

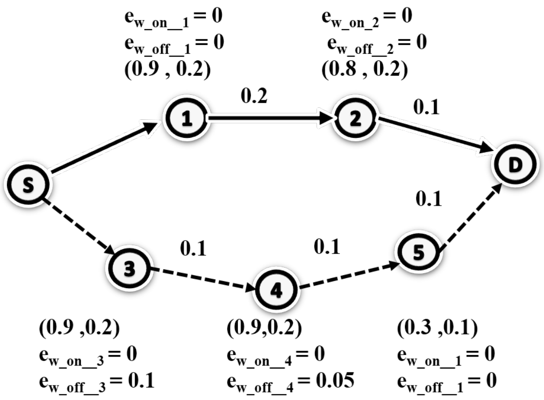

FIGURE 3.3: WAR routing mechanism

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 σ_i and σ_j respectively. The label V_i (x ,y) indicates present battery energy level of x and energy harvesting amount of y in node i over next Δt .Values along with each links represents the amount of energy consumed in respective links if σ_j is used over Δt. However, all energy labels are expressed as a fraction of total battery capacity B. If σ_i is picked as route then the total network energy after route utilization will be 4.2 B and total wastage will be 0.2 B with route cost 0.5 B. While σ_j is used as route then, maximum total network energy of 4.3 B will be achieved with minimum amount of 0.1 B being wasted with minimum route cost of 0.4 B. Equation 3.1, 3.2 and 2.3 defines all this calculation. In this example σ_j is preferable as it leads to minimum wastage and transmission cost. Thus, the consideration of wastage energy in route selection mechanism can leads to maximized total residual network energy. Figure 3.3 depict the fact more specifically.

However,the approach of route cost calculation to maximize the network remaining energy expressed by 2.3 involves a number of complexity.

1. Dependency of route cost calculation on remaining routes information has made it a complex mechanism which results in huge overhead.
2. Requirements of per node information gathering for all off path nodes is mostly impractical specially in case of large network.
3. Moreover, maximizing the network remaining energy does not always ensure perpetual network operation. Always using the lowest energy path may not be optimal from the point of view of network lifetime. Since,overlooking the critical nodes during route selection may cause overload on certain weak nodes. In figure 3.3 energy state in node 5 justifies our claim. Though the route σ_j is promising for maximizing network remaining energy but it does unfair load on weak nodes, resulting early potential death of weaker nodes. Which significantly hampers the assurance of perpetual network operation. Moreover, such scenario is very usual in case of nodes closer to sink nodes in a large network with high data rate. Hence, maximizing the minimum energy level in network is of equal importance.

However,minimization of energy consumption and maximization of minimum energy level in network may be two contradicting goals in some cases. Thus a trade of is essential to get the both benefit proportionally.

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

1. Minimization of Total Network Energy Wastage involving minimum overhead.
2. Minimization of Energy Consumption
3. Maximization of Minimum Energy Level
4. Acquiring a Balanced Position between
    (a) Minimization of Energy Consumption and Maximization of Minimum Energy Levels

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

1. Best feasibly Utilizing the Wastage Energy and thus Minimizing the Wastage amount in Network
2. Minimizing the Energy Consumption due to data delivery in Network.
3. Maximizing the Minimum Energy Levels in network and thus ensuing Balanced Energy Depletion
4. Acquiring a Balanced Position between
    (a) Minimization of Energy Consumption and Maximization of Minimum Energy Levels
5. Assurance of above goals involving minimum overhead.

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. The proposed routing metrics for EH-WSN are discussed with illustrative figures at each of the relevant stages.

4.2 Proposed Metric

Satisfaction of following goals will enable us to formulate our desired routing metric for EH-WSNs. From a set of routes σ we have to select a route σ_n which,

1. Causes Minimum Energy Cost in network
2. Balances Energy Depletion in network

4.2.1 Minimization of Energy Cost

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. Instead of minimum wastage calculation if we focus on the consequence of best feasible utilization of wastage energy, the issue become very simple and appropriate. The outcome of best feasible utilization of wastage energy is the minimum energy depletion from battery. The energy depletion in a node can be defined by following equation.

$$e_i{}^*(\sigma_n) = \begin{cases} max(0, (B - e_i + e_{h\_i} - e_{c\_i}) & e_i + e_{h\_i} > 1 \\ \\ e_c & e_i + e_{h-i} \leq 1 \\ \end{cases}$$

Moreover, minimum energy depletion from battery is the ultimate reflection of appropriate consideration of all the following properties.

- Battery Residual Energy
- Predicted Harvest Energy
- Estimated Energy Consumption
- Channel Condition

The less costly path will always results in less energy depletion form batteries along that route.

Following enclosed example will elucidate our claim. The initial battery level on *node i* is 0.9 B and predicted harvest amount within next Δt is 0.2 B. The expected energy cost within next Δt for being used in route for subtree nodes is 0.1 B. Hence, use of node i in route σ_n will cause zero energy depletion from actual battery since it will utilize the wastage amount of 0.1 B. On the other hand, in *node j* predicted harvest amount within next Δt is 0.1. The expected energy cost within next Δt for being used in route for subtree nodes is 0.1 B. Hence, use of node j in route σ_n will cause 0.1 B energy depletion from actual battery, since there will be no excess of energy.

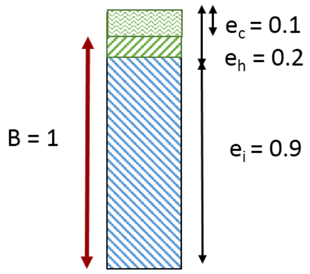

FIGURE 4.1: Battery Level on *node i*

Whenever from a set of routes σ, a route σ_n collectively causes minimum battery energy depletion , then it guaranties the best feasible utilization of wastage energy and selection

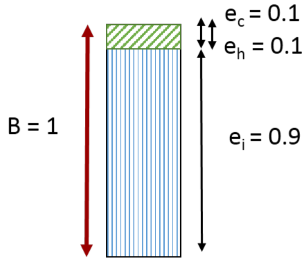

FIGURE 4.2: Battery Level on *node j*

of minimum cost path for next Δt period. If $e_{w\_off\_i}$ is the wastage amount in node V_i before utilized by route ,

$$e_{w\_off\_i} = max(0, e_i + e_{h\_i} - B) \tag{4.1}$$

therefore, current residual energy on node V_i can be expressed by equation

$$e_i{}^* = e_i + e_{h\_i} - e_{w\_off\_i} \quad v_i \not\in \sigma_n \tag{4.2}$$

Thus consideration of minimum energy depletion along a route is enough for assurance of minimum network wastage, maximized network remaining energy.Thus,to satisfy our first goal, we define our routing metric *Energy Depletion (ED)* where the cost function for any route σ_n is

$$\begin{aligned} ED_n &= C(\sigma_n) \\ &= \sum_{v_i \epsilon \sigma_n} e_{ed\_i} \end{aligned}$$

4.2.1.1 Proof of Concept

Residual Energy on node V_i can be expressed as

$$\begin{aligned} e_i^* &= e_i + e_{h-i} - max(0, e_i + e_{h\_i} - B) \\ &= e_i + e_{h-i} - e_{w\_off\_i} \end{aligned}$$

on the other hand,Residual Energy on node V_i after utilizing route σ_n is defined as following

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

Therefore,
the total Network Resultant Energy after utilizing route σ_n is
= (Network Residual Energy - Actual Energy Depletion for route σ_n)

$$\begin{aligned} \sum_{\forall v_i} e_i{}^*(\sigma_n) &= \sum_{\forall v_i}(e_i{}^*) - C(\sigma_n) \\ &= \sum_{\forall v_i}(e_i{}^*) - \sum_{v_i \epsilon \sigma_n} e_{ed\_i} \end{aligned}$$

Our proposed routing metric ED aims to select a route σ_n) form a set of routes Φ which results in maximized total network resultant energy. Therefore, our route selection strategy can be modeled as

$$\sigma_n{}^* = argMax_{\,\sigma_n \epsilon \Phi} \sum_{\forall v_i} e_i^*(\sigma_n)$$

where $\sigma_n{}^*$ is the selected route. Since $\sum_{\forall v_i}$ does not vary because of route selection thus, the objective of our route selection strategy can be modeled as following

$$\sigma_n{}^* = argmin_{\,\sigma_n \epsilon \Phi} \; C(\sigma_n)$$

$$C(\sigma_n) = \sum_{v_i \epsilon \sigma_n} e_{ed\_i}$$

Following example clarifies both the simplicity and efficiency of wastage energy minimization in network. In the sample network shown in Figure 4.3, 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 σ_i and σ_j respectively. The present battery energy level and energy harvesting amount of in node are listed along each *node i*.Values along with each links represents the amount of energy consumed in respective links with next Δt period. However, all energy labels are expressed as a fraction of total battery capacity *B*. If σ_i is picked as route then the total network energy after route utilization will be 4.5 B and total battery energy depletion will be 0.2 B. However, the total network wastage will be 0.15 B. While σ_i is used as route then, maximum total network energy of 4.55 B will be achieved with minimum amount of 0 B being wastage and 0 B being depleted from actual battery. Thus, consideration of actual battery energy depletion ultimately select the route that minimize the total network energy wastage and maximize the network remaining energy.

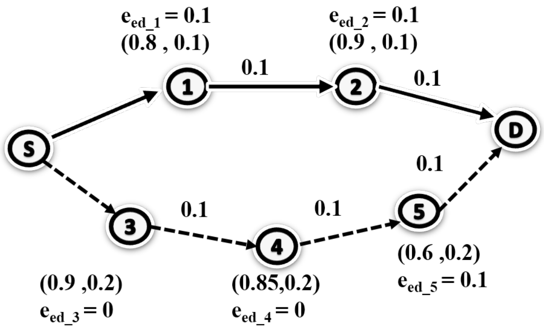

FIGURE 4.3: Sample Network

Moreover, route cost for any route σ_n no more depends on remaining routes in network and no per node information is necessary, which signifies the easiness of the overall mechanism with efficiency.

4.2.2 Balance of Energy Depletion

Our 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 .

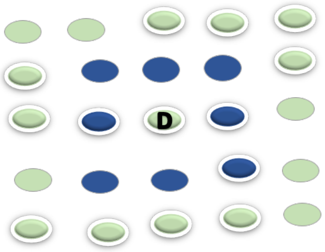

FIGURE 4.4: Energy Burden on Nodes Closer to Sink

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 4.5 is enclosed. Though the energy depletion,e_{ed} in both *node i* and *node j* shown in figure 4.5 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*.

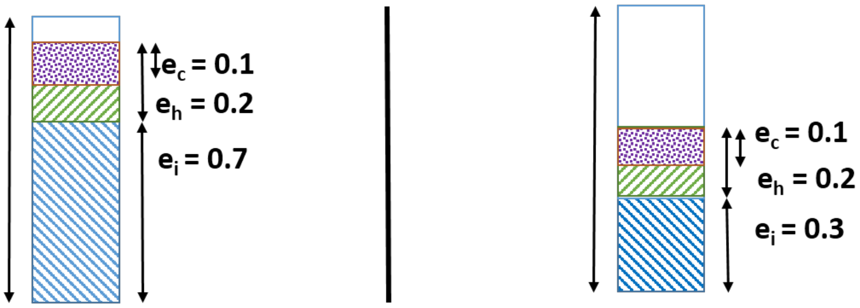

FIGURE 4.5: Fraction of Energy Depletion on node i (a) and node j (b)

Hence,to meet our second goal, we define our routing metric *Fraction of Energy Depletion (FED)* where the cost function for any route σ_n is

$$\begin{aligned} FED_n &= C(\sigma_n) \\ &= \sum_{v_i \epsilon \sigma_n} \frac{e_{ed\_i}}{e_i + e_{h\_i} - max(0, e_i + e_{h\_i} - B)} \\ &= \sum_{v_i \epsilon \sigma_n} \frac{e_{ed\_i}}{e_i^*} \\ &= \sum_{v_i \epsilon \sigma_n} e_{fed\_i} \end{aligned}$$

Following example clarifies the concept of energy deletion balancing in network. In the sample network shown in Figure 4.6, 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 σ_i and σ_j respectively. If σ_i is picked as route then after route utilization total battery energy depletion will be 0.2 B which is 20% of a battery capacity. If σ_j is used as route, minimum amount of 0.1 B will be depleted from actual battery but fraction of energy depletion will be 33% of a battery capacity. Therefore, selection of σ_i as route will allow

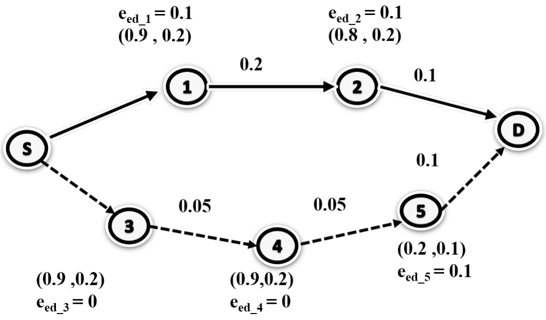

FIGURE 4.6: Sample Network

the weak node in route σ_j to get recharged and become strong. Thus, consideration of fraction of actual battery energy depletion ultimately select the route that balances the energy depletion in network.

4.2.3 Balanced Trade off between Balance of Energy Depletion and Minimization of Energy Cost

However,balancing the Energy Depletion may forces our routing metric to choose a higher energy cost route. Thus, minimization of energy consumption and maximization of minimum energy level in network may be two contradicting goals in some cases. Thus a trade off is essential to get the both benefit proportionally. Equally weighted consideration of both the route cost and fraction of energy depletion can define a balanced position in between this two goals.

Thus, now we have two proposition in our hand.

1. If route cost is too high for a route σ_n than route σ_n should be avoided to reduce the energy consumption in network.
2. If fraction of energy depletion on a route σ_n is too high than route σ_n should also be skipped to uphold the minimum energy level in network.

However, transmission cost is the one of the prominent element which significantly influence the route cost. And transmission cost in any route reflects the channel condition in that route. In a good channel condition the transmission cost on a route is usually low and reverse case is also valid. Hence, we use another widely used metric ETX in our routing metric to meet our final goal. Where, ETX, the expected number of transmission count is the entity which tells us the expected number of transmission required for the same packet, which ultimately reflects the channel condition.
The product of Fraction of Energy Depletion and path ETX in a route σ_n represents such a metric which magnifies the domination of either one based on their contribution level. Thus, The product of Fraction of Energy Depletion and path ETX in a route σ_n can be used to come to a balanced position in between our goal one and two. Such product proves the domination of transmission cost over its energy depletion level in a route ,when the transmission cost is really too high. On the other hand it will also reflect the supremacy of level of energy depletion in a route over it's transmission cost where the level of energy depletion in that route is significantly high.

Therefor, choosing a route which collectively results in minimum product of fraction of energy depletion and path ETX promises a balanced position between maximization of network remaining energy and maximization of minimum energy level in network.

Hence, we define the Prioritized Fraction of Energy Depletion (PFED) on node i as

$$e_{pfed\_i} = e_{fed\_i} * ETX_{if} \qquad v_j \epsilon \sigma_n, v_i \epsilon \sigma_n \tag{4.3}$$

and v_j is immediate upstream node of v_j
Hence,to meet our final goal , we define our final routing metric *Prioritized Fraction of Energy Depletion (PFED)* where the cost function for any route σ_n is given by following equation

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

4.3 Implementation Issue

In this section we are going to discuss the detail procedure of implementation of our proposed routing metrics in a routing protocol.

The cost function implementation of our routing metrics demands a number of information component gathered by routing protocol. Required information component to implement ED,FED and PFDE are listed below.

1. e_i , Current energy level in node V_i
2. e_{h_i} , Predicted harvest energy over Δt in V_i
3. e_{h_i} , Predicted energy consumption over Δt in V_i
4. etx_{i_j}, Link etx between V_i and V_j

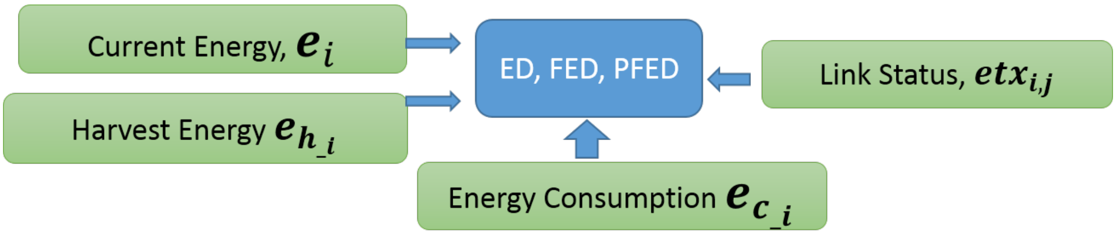

Figure 4.7: Required Information on each Hop

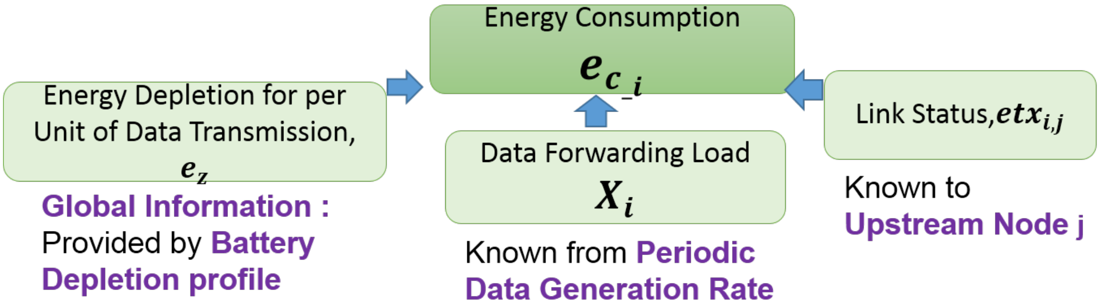

FIGURE 4.8: Calculation of Energy Consumption

4.3.1 Implementation of Metrics on Dynamic Sources Routing Protocol

We apply our routing metrics ED, FED and E-FED on DSR(Dynamic Source Routing) by introducing little modification into the DSR framework.

4.3.2 Energy Information Gathering

In modified DSR, sink node collects necessary network information during route discovery phase and formulate the cost value for each route. On-path energy information can be obtained cumulatively along the route using RREQ cost fields. Route request packets are broadcast in network during route discovery phase. Per hope energy state information are put inside new RREQ header append with RREQ packet. Sink node takes the opportunity of taking optimal decision based on collected information by Route Request Packets (RREQ pkt). However, dynamic source routing is not carried out for each and every data packet. Rather established routes remain valid till Δt period. Any route also become invalid after disagreement form any node in route. Once a node is in energetically threaten condition, it can disagree to forward others data.

RREQ packet collects following information in every hop is traversed in a rote σ_n.

1. $e_i + e_h$, Residual Energy in node V_i
2. x_i , Data Forwarding Load over Δt in V_i
3. etx_{i_j}, Link etx between V_i and V_j
   (a) Immediate Receiver j puts the Link etx_{i_j}

Information gathering at every nodes in any rote for cost calculation is depicted by figure 4.9.

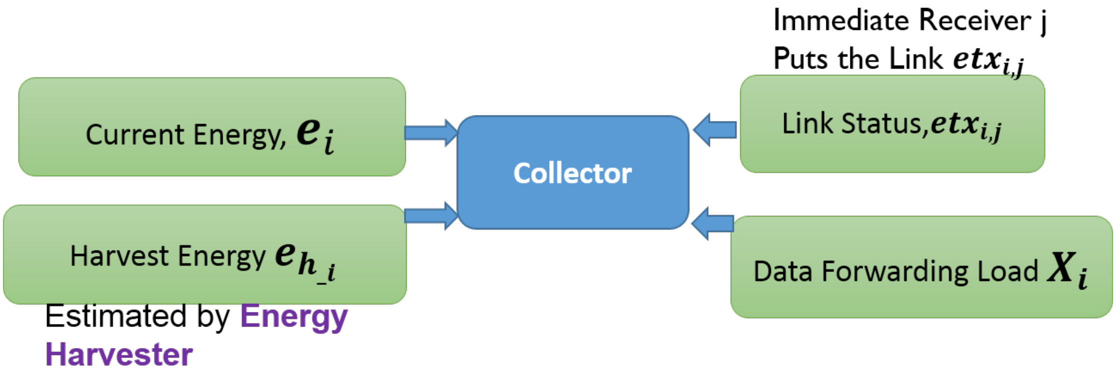

Figure 4.9: Information Gathering at Each Hop

4.3.3 Route Selection at Sink

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. DSR 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.

Chapter 5

Simulation Result and Performance Analysis

5.1 Introduction

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

5.2 Simulation Requirements

To implement the appropriate environment for energy harvesting wireless sensor network a number of issues need to be addressed. Among them followings are mentionable

1. Battery depletion profile of Energy harvesting sensing devices
2. Energy harvest profile of Energy harvesting sensor devices

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.

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

FIGURE 5.1: Telosb Mote used in Testbed implementation

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%

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.

5.2.2 Energy Harvesting Profile

In energy harvesting systems, the availability of harvested energy could significantly vary with the weather conditions. Such variation is predictable in many cases. In this situation, an accurate predictor allows the system to make critical decisions about the efficient utilization of the available energy. Therefore, many researchers have explored accurate predictions of harvested energy [19], [20]. Most of these studies have assumed that weather conditions can be precisely predicted using past weather data [19], [20]. Some researches argue against this claim. According to their claim, predictions derived from weather forecasts are more accurate at medium-length timescales, i.e.,hours to days [21].However, unavailability of energy harvesting sensor motes at present has restrained us to use any real time prediction algorithm.

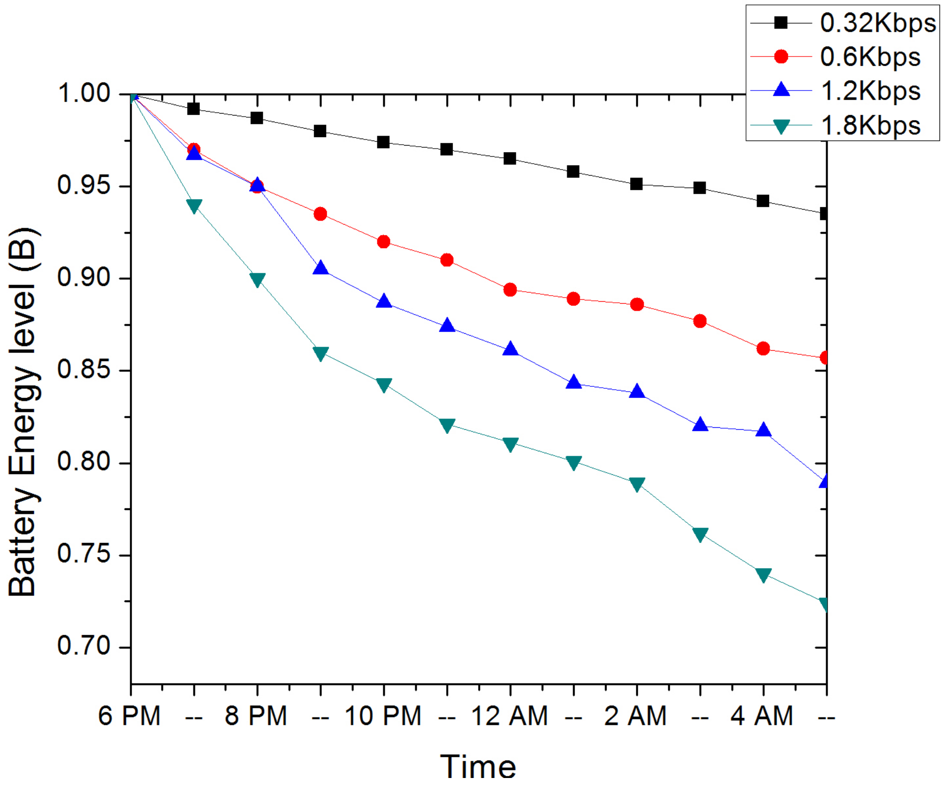

FIGURE 5.2: Battery Depletion Nature of Telosb mote at different data rate

TABLE 5.2: Sample Energy Harvest Rate

Slot name	Duration	Minimum Harvest amount /Hour	Maximum Harvest amount /Hour
Period -A	06.00 AM-08.00 AM	0 B	0.01 B
Period -B	08.01 AM-09.59 AM	0 B	0.03 B
Period -C	10.00 AM-11.59 AM	0.009 B	0.069 B
Period -D	12.00 PM-02.59 PM	0.022 B	0.099 B
Period -E	03.00 PM-04.00 PM	0.001 B	0.01 B

[18] provides a case study in solar radiation and the potential evaluation of solar energy harvesting at 6.431N, 100.185E, in Kangar, Perlis, Malaysia. We have used a sample and constant energy harvesting profile based on the suggestion of [19], [20],[21] and explained in table 5.2. However, we adopted a harvest profile which contributes limited amount of harvest energy in harvesting devices. According to our harvest profile mentioned in table 5.2 on average a harvesting device can recharge its 15% to 20% of battery by harvest energy in a single day. We have done so just to check the strength of our metrics.

In addition of that, we have also used two different per day harvest plan to check the strength of our routing metric in variable environment.Table 5.3 and 5.3 describes those.

Table 5.3: Per Day Harvest Plan-1

Day	Harvest Nature
Day 1	Limited Harvest
Day 2	Harvest
Day 3	Harvest
Day 4	Zero Harvest
Day 5	Zero Harvest
Day 6	Harvest
Day 7	Harvest
Day 8	Zero Harvest
Day 9	Zero Harvest
Day 10	Zero Harvest
Day 11	Harvest
Day 12	Zero Harvest
Day 13	Zero Harvest
Day 14	Zero Harvest

Table 5.4: Per Day Harvest Plan-2

Day	Harvest Nature
Day 1	Limited Harvest
Day 2	Harvest
Day 3	Harvest
Day 4	Zero Harvest
Day 5	Zero Harvest
Day 6	Harvest
Day 7	Harvest
Day 8	Harvest
Day 9	Harvest
Day 10	Zero Harvest
Day 11	Zero Harvest

5.3 Simulation Setup

- We have used ns-3 as our simulator.
- 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

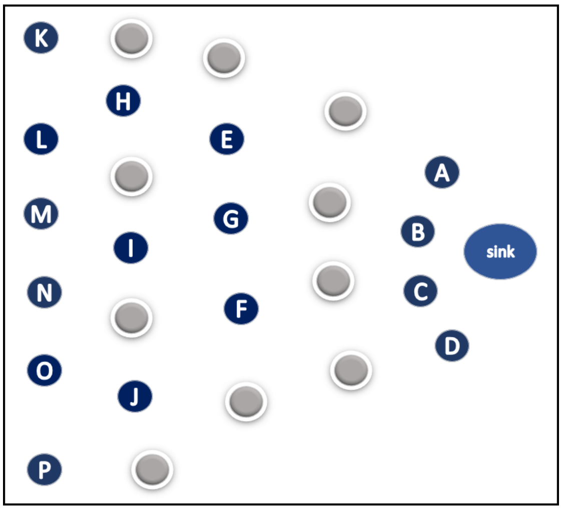

FIGURE 5.3: Sample Topology

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 :**30 meter
- **Packet size :**128 bytes

Now we evaluate the results of ED, FED PFED in various data rate.

5.4 Performance Analysis

We first consider the topology shown in figure 5.3 with 27 nodes in a tree like arrangement. Darken nodes generates CBR data with data rate of 0.13 Kbps destined to sink. All the nodes follows the per day harvest plan 1 described at table 5.3. For the clarification of power of proposed routing metrics, we have considered the EH-sensor nodes first death as permanent death. Though in real EH-WSNs it will alive again once the harvesting energy become available.

Figure 5.4 shows the network average of residual battery levels normalized to B while using WAR[5][17], ED as routing metric respectively. In both case network average energy level is observed as similar, since both of their route cost function tries to minimize the energy consumption by reducing wastage of energy. Both of them maximize the network remaining energy.

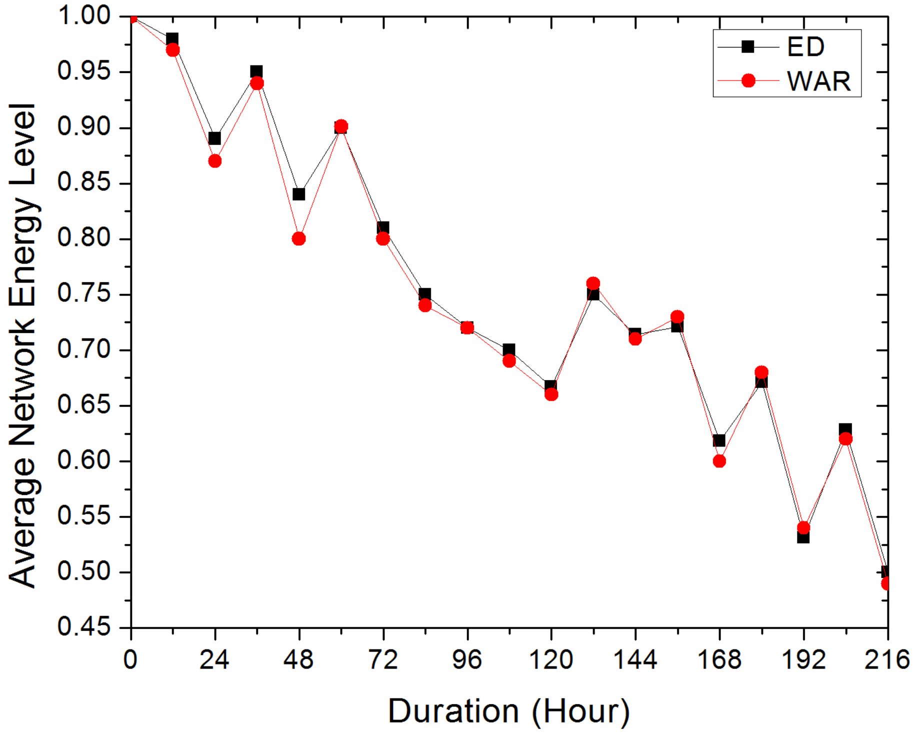

FIGURE 5.4: Average Battery level in WAR and ED

Figure 5.5 shows the minimum energy level in network while using WAR[5][17], FED as routing metric respectively. Figure 5.5 justify the appropriate outcome of routing metric FED which maximize the minimum energy level higher than WAR. The first node temporary dies after 204 hours is passed, on the other hand in FED at 204 hour minimum energy level is moderately good and it is almost 35% of total battery energy. In case of FED the first node temporary dies after 312 hour is passed and after tolerating long non harvesting days. Day 8 to day 14 are fully non harvesting days except only day 11 [table 5.3]. Thus FED can avoid temporary death of EH-sensors and ensure perpetual network operation.

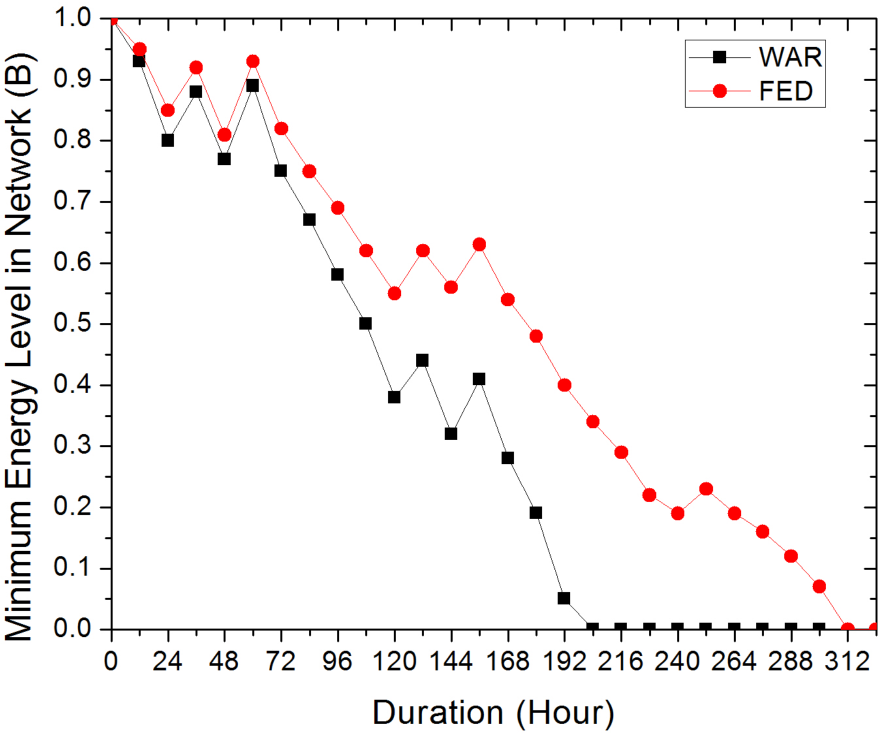

FIGURE 5.5: Minimum Battery level in WAR and FED

Figure 5.6 shows the average energy level in network while using WAR[5][17], FED as routing metric respectively. Figure 5.6 shows that, average energy level in case of FED is almost same like WAR at the beginning days. Though after 96 hour , the average level is below since during that time, FED sacrifices energy consumption and give preference to weak nodes. Thus, during that phase the minimum energy level of FED is much higher than WAR. However FED average energy level is higher after 192 hour is elapsed. Since after that, few nodes in WAR has ready experienced temporary death. Figure 5.7 shows the life time of WAR and FED.

In Figure 5.8, it can be seen that, in case of PFED the minimum energy level is still above than WAR. Since it is not unconcerned of weaker nodes. Figure 5.8 shows that, PFED can not maximize the minimum energy level but do not even over look. Rather it goes to almost closer of maximized minimum energy level. Figure 5.8 demonstrate the comparative network life time of WAR, FED and PFED.

In Figure 5.11, it can be seen that, in case of PFED the average energy level is almost same like WAR at the beginning. Average energy level of PFED deteriorates after 96 hour has elapsed, since in that moment it gives priority to weaker nodes even tolerating higher energy consumption. Figure 5.12 shows that, though the average energy level

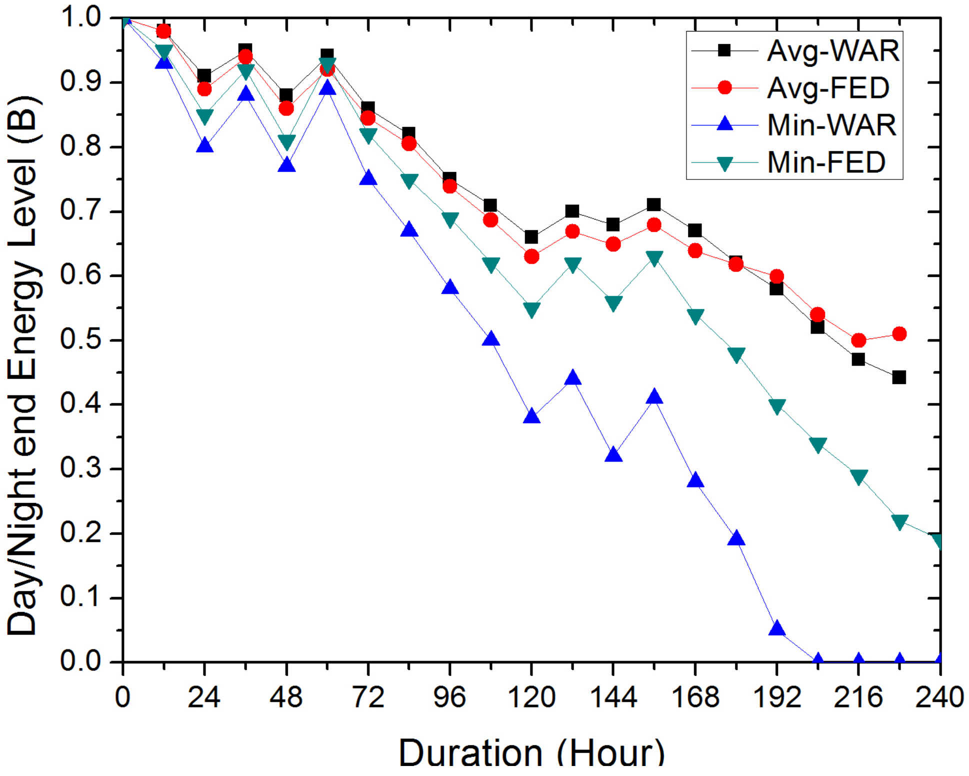

FIGURE 5.6: Minimum and Average Battery levels in WAR and FED

time.jpg time.jpg

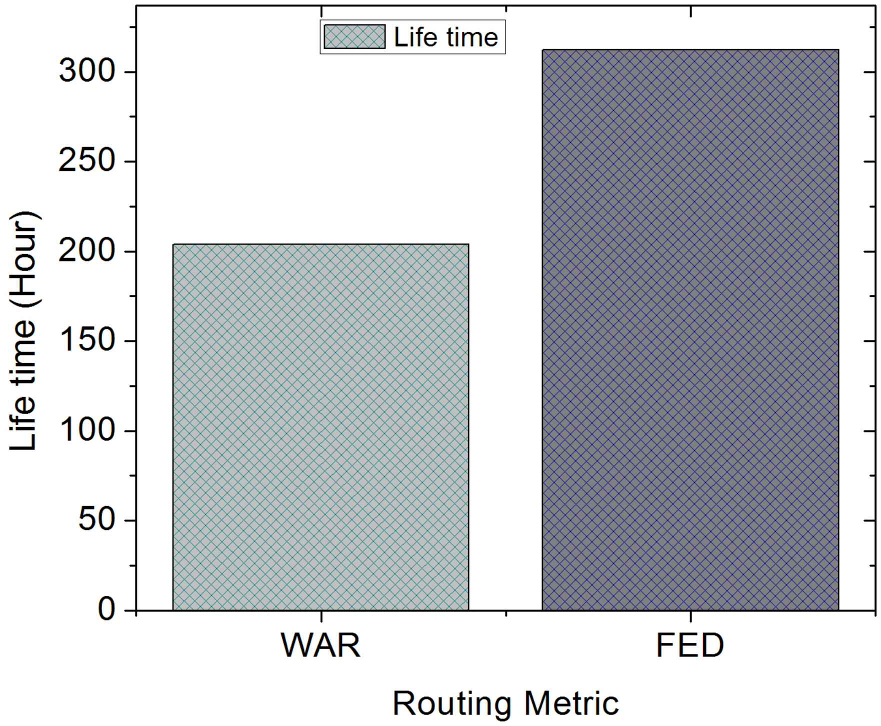

FIGURE 5.7: Network Life Time of WAR and FED

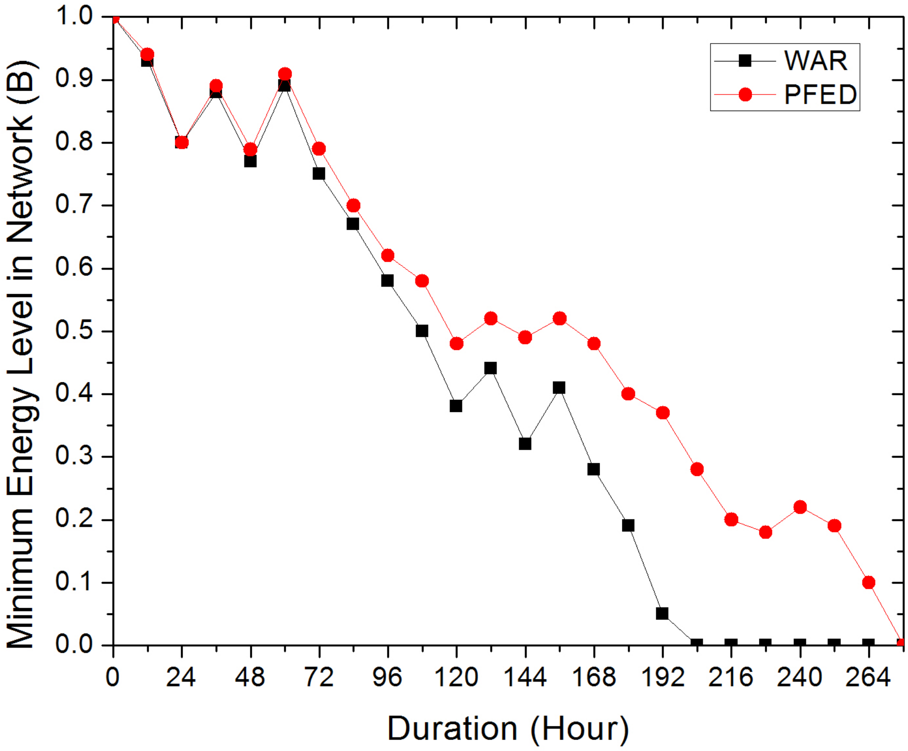

FIGURE 5.8: Minimum Battery level in WAR and PFED

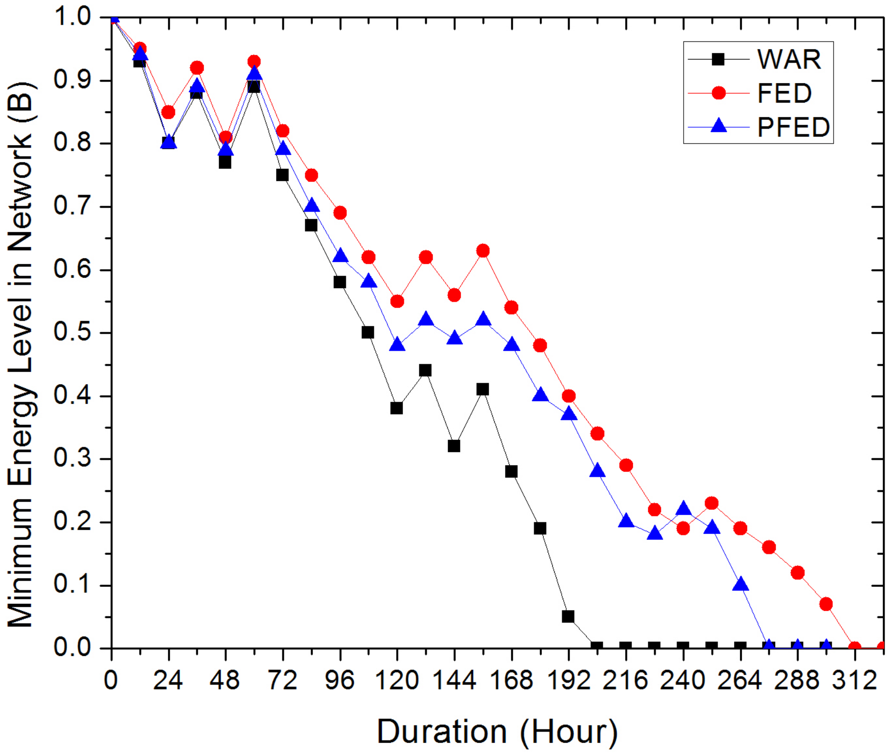

FIGURE 5.9: Minimum Battery level in WAR, FED and PFED

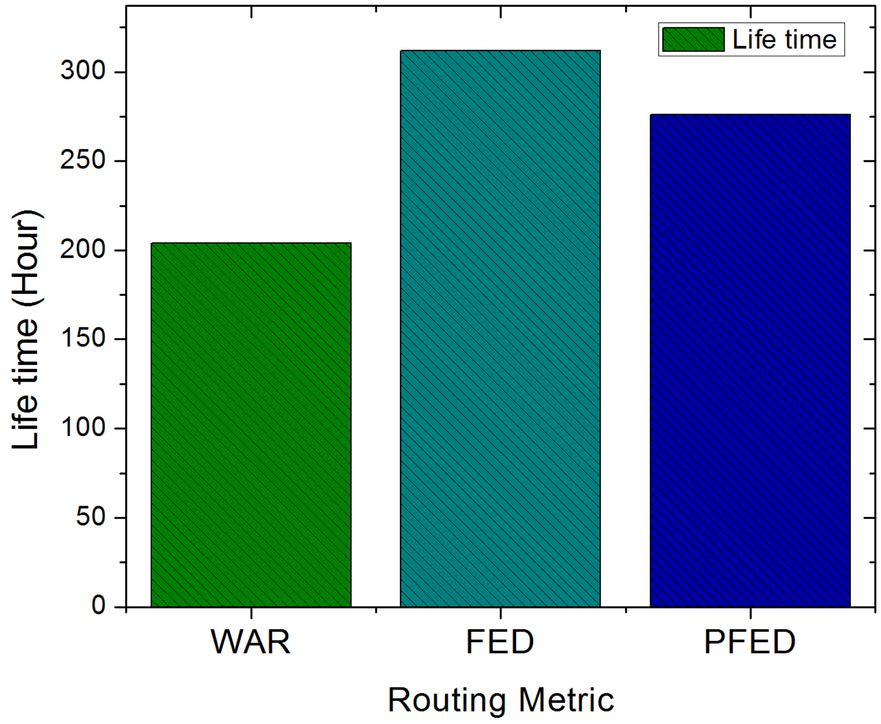

FIGURE 5.10: Network Life time in WAR, FED and PFED

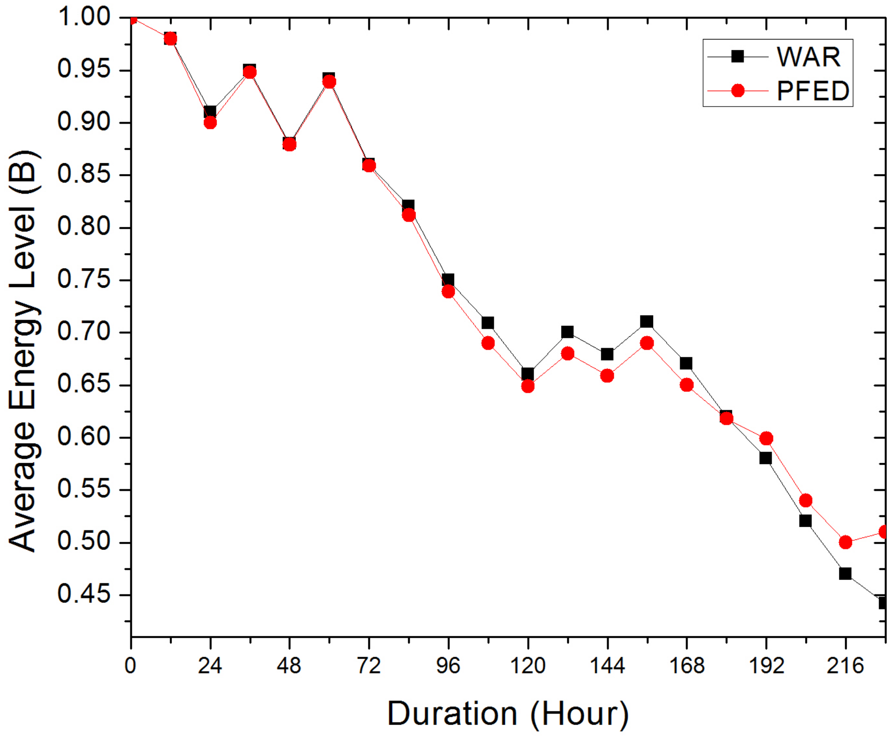

FIGURE 5.11: Average Battery level in WAR, and PFED

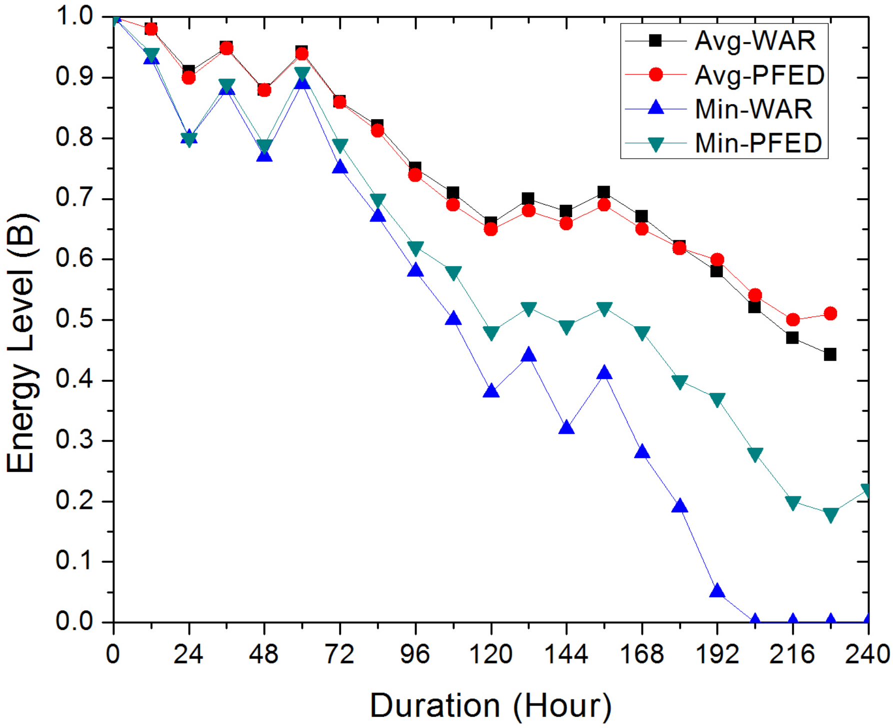

Figure 5.12: Minimum and Average Battery level in WAR and PFED

of PFED is low than WAR but it has much higher minimum energy level during those moments.

In WAR minimum energy level in network is always low and temporary dies early, the reason behind this will be justified by figure 5.13 . In this case per day harvest plan 2 is applied. Since WAR only look for minimum cost path, hence it go for always minimum cost path. In case of node B and node c, perhaps through them the route was less costly comparatively to through node A and D. Which may lead to unbalanced energy depletion in network. However such case is not expected in our case . Figure 5.14 shows the enegy levels of same nodes while using FED.

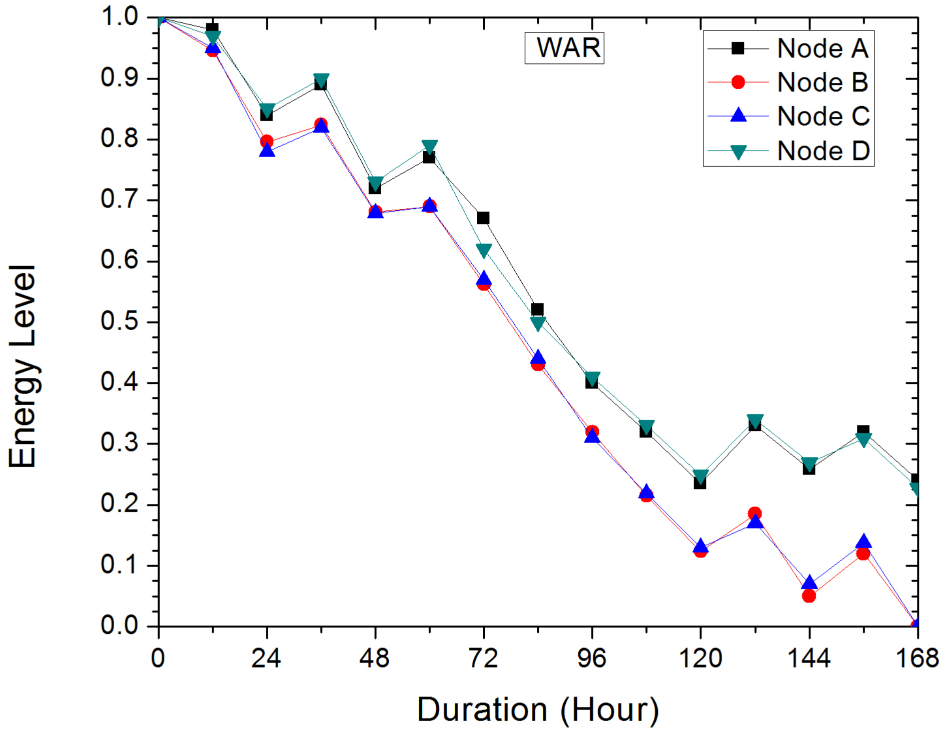

FIGURE 5.13: Energy levels of nodes closer to sink while using WAR

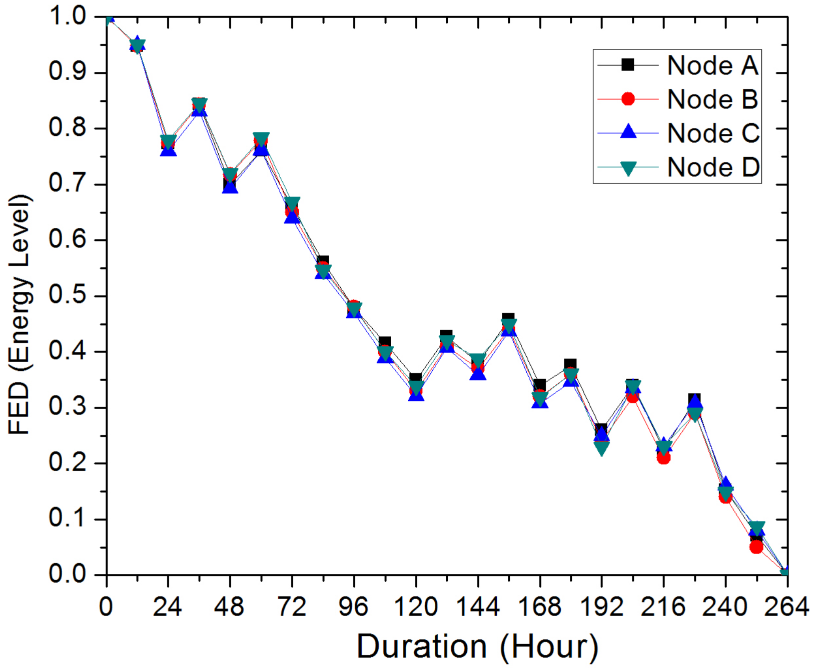

FIGURE 5.14: Energy levels of nodes closer to sink while using FED

Chapter 6

Conclusion

6.1 Summary of Contributions

We proposed routing metric ED energy depletion which minimizing the wastage of energy in network with minimum overhead. And thus maximizes the total network remaining energy. Further, routing metric FED eliminates the unbalanced energy depletion problem. Finally our routing metric PFED achieves both benefits proportionally.

6.2 Future Work

Furthermore, performance of our routing metrics will be further improved if it is implemented in CTP like routing protocol, where each and every node distributively pick the best route. Thus, implementation of ED, FED and PFED in CTP is left as future work.

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