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KARTIK SHARMA
RADIO ACCESS TECHNIQUES FOR ENERGY EFFICIENT AND ENERGY HARVESTING BASED WIRELESS SENSOR NETWORKS

Master of Science thesis

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Examiner and topic approved by the
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ABSTRACT

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Traditional Wireless Sensor Networks (WSN) rely on batteries with finite stored energy. In the future with billions of such devices, it will be difficult to replace and dispose their batteries, which can cause a huge environmental threat. Hence, research is being done to eliminate batteries from sensor devices and replace them with harvesters. These harvesters can power the sensor network nodes by extracting energy from ambient sources. Harvesters are already being implemented in many real-life applications like structural health monitoring, environment monitoring and body area networks. A sensor network of multiple energy harvesting enabled devices is known as Energy Harvesting based Wireless Sensor Network (EH-WSN).

For uninterrupted operation of EH-WSN, radio protocols must consider the energy harvesting constraints; (i) energy harvesting process unpredictability and; (ii) energy harvesting rate variations in time and space. EH-WSN comes with unique traits which discourage the use of existing WSNs radio protocols, as most of existing protocols are focussed on decreasing the energy consumption and increasing the network lifetime. This thesis work focusses on modifying an existing energy-efficient Multipath Rings (MPR) routing protocol for low-power and low-bandwidth EH-WSN and evaluating its performance through simulations. Firstly, the topology setup phase is revised by implementing a new ring formation scheme for better data reliability. Secondly, controlled flooding of data packets is used by enabling selective forwarding, which leads to decrease in network traffic and overall energy consumption. Lastly, every node is equipped with a neighbors' table on-board which helps in making energy-related routing decisions in multi-hop networks. A periodic energy update packet transmission helps in keeping latest neighbor information. This modified version of MPR routing protocol is called Energy Harvesting based Multipath Rings (EH-MPR) routing. This work also provides a comprehensive survey on existing MAC and Routing protocols for energy efficient and energy harvesting based WSNs.

Through this work, the main constraints on using existing energy-efficient protocols for EH-WSN are discussed and depicted with the help of network simulations. The effects of using fixed duty cycle for energy harvesting enabled sensor nodes are outlined by simulating T-MAC (adaptive duty cycle) against S-MAC (fixed duty cycle). For all evaluation metrics, T-MAC outperformed S-MAC. Using Castalia's realistic wireless channel and radio model, EH-MPR is simulated for low-power, low-data rate and low bandwidth (1 MHz) networks where satisfactory results are obtained for sub-GHz frequencies (433 MHz and 868 MHz). Next, the modified EH-MPR protocol is compared with original MPR routing under practical deployment scenarios. The metrics in consideration are successful packet transmissions, energy consumption, energy harvested-to-consumed ratio and failed packets. After thorough simulations, it was concluded that although the packet success rate is approximately equal for both protocols, EH-MPR has advantages over original MPR routing protocol in terms of energy cost and uninterrupted operations.

PREFACE

This thesis is written in partial fulfilment of the requirement for the Master of Science degree in Electrical Engineering, at the Department of Electronics and Communications Engineering, Tampere University of Technology, Finland. All the research and investigations covered under this work are done at ELT department, under the supervision of Prof. Mikko Valkama and Lic.Sc(Tech.) Jukka Rinne.

I would like to express my sincere gratitude to my esteemed supervisor, Jukka Rinne, who has helped me throughout this research. His valuable insight and suggestions worked as a catalyst for the success of this work. I would also like to thank Prof. Mikko Valkama for providing me with the opportunity to work in this excellent research project and for all necessary support.

My appreciation goes to my mother Ranjana Sharma, my father Rajendra Sharma and my sister Nitika Sharma whose constant support and affection have always been an inspiring and motivating factor for me. I also take this opportunity to thank my friends in Tampere University of Technology and back in India for their generous help and precious friendship, specially Melissa, Sutirtho and Ajith who believed in my graduation more than I did.

I dedicate this thesis to them all.

Kiitos!

Tampere, 19.10.2016

Kartik Sharma

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

IEEE	Institute of Electrical and Electronics Engineers
WSN	Wireless Sensor Networks
IoT	Internet of Things
M2M	Machine to Machine
WIA-PA	Wireless Networks for Industrial Automation-Process Automation
BS	Base Station
GW	GateWay
OSI	Open System Interconnection
DLL	Data Link Layer
MAC	Medium Access Protocol
LLC	Logical Link Control
QoS	Quality of Service
TDMA	Time Division Multiple Access
CSMA	Carrier Sense Multiple Access
LEACH	Low-Energy Adaptive Clustering Hierarchy
GPS	Global Positioning System
EH	Energy Harvesting
EH-WSN	Energy Harvesting based Wireless Sensor Networks
ENO	Energy Neutral Operation
ENO-max	Energy Neutral Operation - Maximum
RF	Radio Frequency
PV	PhotoVoltaic
RF-EH	Radio Frequency based Energy Harvesting
MPR	MultiPath Rings
EH-MPR	Energy Harvesting based MultiPath Rings
T-MAC	Timeout-Medium Access Protocol
S-MAC	Sensor-Medium Access Protocol
RTS	Request To Send
CTS	Clear To Send
ACK	Acknowledgement
SYNC	Synchronization
TA	Activation Timeout
ODMAC	On Demand Medium Access Protocol

PSM	Power Saving Mode
CW	Contention Window
AP	Access Point
CH	Cluster Head
CM	Cluster Member
RSSI	Received Signal Strength Indicator
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
ADV	Advertisement
AODV	Ad-hoc On-demand Distance Vector
AODV-EHA	Ad-hoc On-demand Distance Vector - Energy Harvesting Aware
RREQ	Route REQuest
RREP	Route REPly
TX	Transmitter
RX	Receiver
BAN	Body Area Network
SINR	Signal to Interference-plus-Noise Ratio
SNR	Signal to Noise Ratio
BER	Bit Error Rate
CPU	Central Processing Unit
NED	NEtwork Description
EWMA	Exponentially Weighted Moving Average
WCMA	Weather-Conditioned Moving Average
PSK	Phase-Shift Keying
BW	BandWidth
MHz	MegaHertz
GHz	GigaHertz

1. INTRODUCTION

Energy harvesting in wireless sensor networks is a promising research area but it comes coupled with complex research challenges. Even though EH-WSN deals with the problem of energy constraints, the available power levels from the state-of-the-art energy harvesters are quite small, i.e., 1 to 50 μW (indoors) or several mW (outdoors) which are inadequate to power a wireless sensor node continuously [3]. For instance, a TI CC2240 transceiver [26] requires 52.4 mW to transmit and 49.2 mW to receive packets. Low harvesting rates necessitates the network architect to implement low duty cycling operation. Low duty cycling nodes are ideal for monitoring applications where node transmissions is not a continuous process. Many environmental factors are responsible for varying energy harvesting rates. The type and size of harvesters also influence the harvesting rates. For example, the solar energy harvesting is maximum in noon but is comparatively lower in mornings and evenings. Also, a larger solar cell area can harvest more energy when compared to a smaller sized solar cell. Node mobility is another factor (e.g. vehicular sensor networks [19]) which can increase the complexity of developing and maintaining the wireless network. In EH-WSN, the incoming energy uncertainty poses higher challenges in designing suitable networking protocols. The above mentioned reasons are convincing enough on non-compatibility of existing energy-efficient radio protocols for EH-WSN. Since a battery powered node can work continuously till its battery depletion, the main criteria for creating networking protocol was to extend the network lifetime. These protocols cannot be applied directly to EH-WSN since each node has different residual energy and harvesting rates. Hence, there is a need for new networking protocols focusing on energy harvesting.

1.1 Motivation

WSN is designed for monitoring physical entities or environmental conditions. It is well-established that a major drawback in battery-powered WSN is limited energy

[41] [36]. Once the energy is depleted; node can no longer be used unless its battery is recharged or replaced. At the same time, recharging or replacing batteries in sensor nodes can be expensive, time consuming or not feasible in cases like volcano monitoring [31]. In the future with billions of small battery-operated devices, battery disposal will be an environmental hazard. EH-WSN enables the replacement of disposable batteries with a combination of energy harvester and a storage device to store the harvested energy. Although it sounds quite easy and straightforward, a lot of complications are associated with this solution. The available power levels harvested from the state-of-the-art harvesters are insufficient to operate a sensor node steadily. Due to space constraints, it is not possible to increase the size of energy harvester or to install multiple energy harvesters in a single node. An average rate of energy harvesting is quite low in comparison to the rate of consumption, which needs to be considered while designing the applications and protocols. EH-WSN cannot use the already established protocols as they don't ponder the implications of energy harvesting values. Since a normal battery-powered sensor node can operate until its battery reaches an unusable level, the aim for existing routing protocols is to conserve the energy and extend lifetime. These WSNs are well aware of sleep and wakeup schedules of network nodes which helps in designing energy-efficient routing protocols for multi-hop transmissions. There are multiple energy-efficient routing protocols in literature but these protocols cannot be used with EH-WSN because of following features:

1. Energy harvested is unpredictable and different for different sensor nodes in the network (depending on placement, locations and sizes).
2. Multihop routing is important in low power networks for wide area coverage. But due to different harvesting rates, the sleep and wakeup schedules for EH based nodes will be different. EH-WSN has short and limited transmission range which necessitates the need of multi-hop compatible protocols.
3. Network needs to have prior knowledge of residual energy and harvesting rate in order to make networking decisions.

For example, let us consider a multi-hop routing case where node A transmits to node C via node B or node D where node B and D can act as possible forwarder. If existing protocols are used with EH-WSN, below mentioned reasons can lead to packet loss:

1. Node B or D were sleeping when source node A is transmitting the packet.
2. Node B or node D don't have enough energy to forward the packet to node C.

Hence there is a need for energy harvesting aware routing protocols which can consider the harvesting rate and residual energy for making routing decisions. In above example, node A can choose a potential forwarder if it has prior knowledge on harvesting rate of nodes B and D. The existing routing protocols must be modified for better performance in energy harvesting constraints. *An energy harvested compatible protocol is needed which establishes a balance between energy consumed and energy harvested.*

1.2 Thesis Structure

Chapter2 will introduce wireless sensor networks and energy harvesting technology in sensor networks. Energy-efficient MAC protocols and their application in energy harvesting based networks are reviewed in chapter3. Next, the energy-efficient and energy-harvesting enabled routing protocols are characterized in Chapter4. In chapter5, the proposed "Energy harvesting based Multipath Ring Routing (EH-MPR)" routing protocol is explained by modifying existing energy-efficient "Multipath Rings Routing (MPR)" routing protocol. Chapter6 will contain the performance evaluation of proposed EH-MPR routing protocol using simulations and its comparison with MPR protocol for proving improved operation in energy harvesting environment. At last, Chapter7 concludes this thesis by summarizing the major achievements of this research.

2. FUNDAMENTALS OF WIRELESS SENSOR NETWORKS AND ENERGY HARVESTING

2.1 Wireless Sensor Networks

2.1.1 Definition of WSN and Market Trends

A Wireless Sensor Network (WSN) [10] consists of large number of wireless nodes (sensor nodes) where each node is composed of a transceiver, a battery, micro-controller and a sensor. WSNs are used to gather information from the environment to construct a system which can largely refine the efficiency and reliability of large systems. Being wireless, WSNs are easy to deploy and scale. This matured field of sensor network makes WSN the key technology for Internet of Things (IoT). Currently, wireless sensor networks is an active research area as it promises to make our life easier through Machine-to-Machine (M2M) communications. Intelligent sensor nodes can help us to understand the nearby environment better and can also be used to automate certain manual tasks. It all started in 1970‘s when WSN was first used for military application where sensors were randomly and densely deployed in the field to check for intruders. Covertness and robustness properties were required for proper working in such harsh deployment environment.

WSN can be defined as a network of sensor nodes that senses and controls the environment, which can enable the interactions between humans and the surrounding environment (or computers). WSN usually contains actuator nodes, sensor nodes, gateways and clients. A large number of sensor nodes deployed randomly in a monitoring area (also known as sensor field) can form networks through self-organization. These sensor nodes collect data from the environment and transmit it to the gateway or base station or sink using single-hop or multi-hop techniques. In multi-hop, data is handled by multiple nodes before it reaches the gateway. In Figure 2.1, a target(sender node) is sending data to the sink node in a multi-hop fashion. Sink

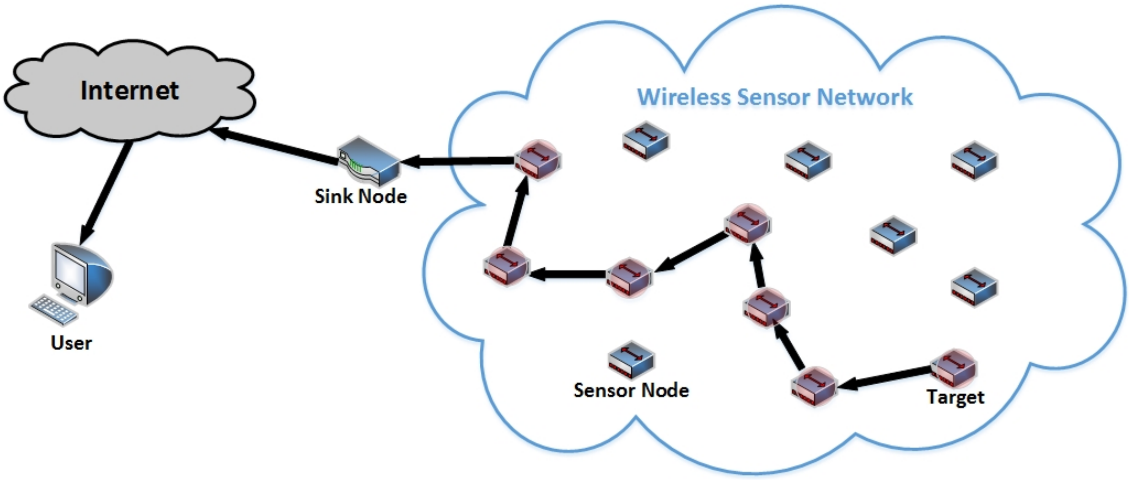


***Figure* 2.1** *Wireless Sensor Networks*

acts as a bridge between the user and WSN using the internet. Sink collects the network data and can transmit it to a distant user through internet.

In WSN, sink acts as a data collecting node. Hence, the location of sink in the network has high impact on energy consumption. To increase the data gathering capabilities of the network, mobile sinks are used which can locate themselves in an area of maximum throughput and with less overall energy consumption. As the related technologies have matured, the cost of developing WSNs has reduced drastically and application area is expanding. Some of the well-established standards of WSN are ZigBee, WirelessHart, Wireless networks for Industrial Automation - Process Automation (WIA-PA) and many more. With more and more new emerging industrial and home applications, new requirements are taking birth and hence, the total market size of WSN applications is growing rapidly.

Both industry and research institutes are making combined effort to solve WSN related problems. Some examples of these collaboration include ZigBee alliance, NASA sensor webs etc. Major aim of such standards organizations is to accelerate the huge deployment of mentioned WSNs in consumer and industrial applications by decreasing the price and power consumption per sensor node, while easing the development by collaborative efforts as shown in Figure 2.2.

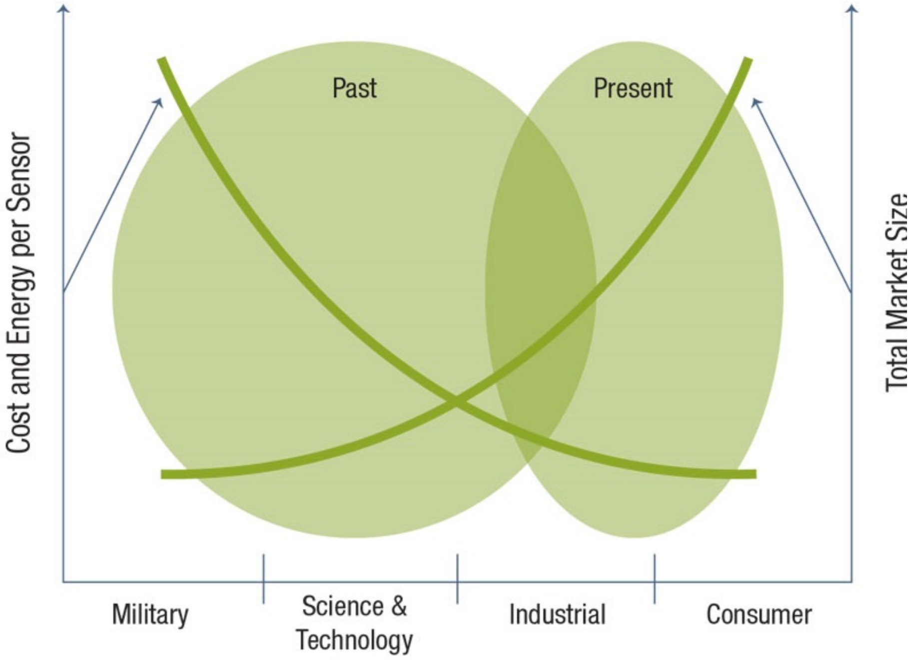


Figure *2.2 WSNs gain market traction with decrease in sensor costs [15]*

2.1.2 Sensor node

WSN is a collection of sensor nodes communicating and transferring data with each other. A standard sensor node contains four main parts as shown in Figure 2.3:

1. A wireless transceiver
2. A microcontroller
3. A sensor
4. Power and power management module

The power module acts as a bridge between power supply and the rest of the circuit. It provides the necessary power required by different components of a sensor node. The sensor in a node initiates the process when it captures some physical information (temperature, acceleration etc.) about the environment. In technical words,a sensor node collects and transforms the signals like illuminance, heat, motion, into electrical signals and then forwards them for further processing to the microcontroller. The job of microcontroller is to process the captured data as required by user. It can choose to process and send further or to discard the sensor reading. The wireless

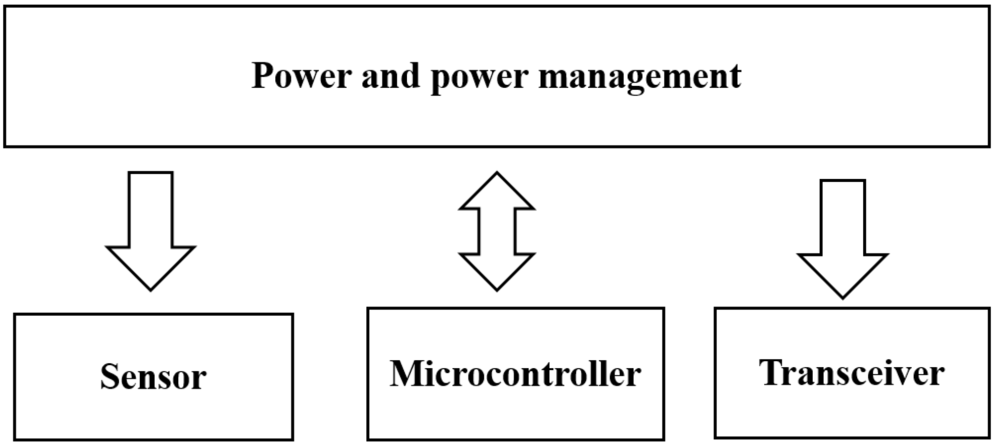


Figure 2.3 *Hardware structure of a sensor node*

transceiver module can transfer the processed data from the microcontroller for the physical realization of communication. Nowadays, main requirements for sensor node are small size and limited power. That is why a large part of WSN research is focussed on energy-efficient radio access protocols. A battery can power a sensor node for a limited time and these are written to make the efficient use of available power.

2.1.3 Examples of WSN

1. *Area Monitoring*: In this application, the sensor nodes are distributed over a region which needs to be monitored. Military [45] and room monitoring [43] are few examples of such application.
2. *Agriculture*: In agriculture applications [8], monitoring the gravity feed water and the pump can be controlled using the wireless input-output devices. Another main objective is to indicate when the field or specific parts of it are at risk of developing fungal diseases.
3. *Healthcare systems*: Smart homecare systems [12] has enabled the remote monitoring and medicine reminders for the patients. In such cases, WSN collects data based of physician’s recommendations and provides continuous record to assist the further diagnosis.

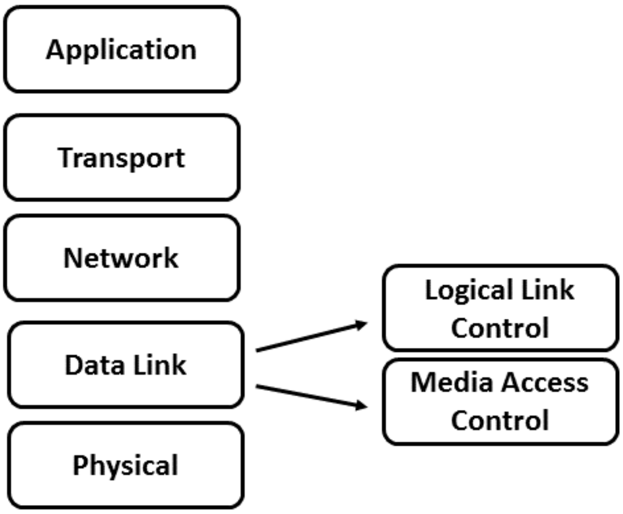


***Figure* 2.4** *Protocol stack of WSN*

2.1.4 WSN Architecture

WSN architecture is based on OSI (Open System Interconnection) layer model. This model is altered to 5 layers for WSNs. The layers are shown in Figure 2.4 and are discussed below:

Physical Layer

Physical layer is the first layer in WSN architecture which is responsible for all radio or signal communications. It consists of networking hardware technologies. For a traditional OSI-ISO model, physical layer is responsible for translating the logical address received from upper layer (data link) as more hardware compatible.

Data Link Layer

This layer is responsible for physical addressing and providing other resources in order to broadcast data among networks. It is also responsible for identifying and correcting the physical layer errors. Other tasks include frame synchronization, encoding and decoding of data. As evident from Figure 2.4, Data link layer can be categorized into two sub-layers:

1. *Media Access Control (MAC)*: This sub-layer takes care of channel access mechanism and addressing tasks. MAC enables multiple nodes to communicate in shared channel environment. MAC address is added to the end of data frame and in the beginning of the next frame.
2. *Logical Link Control (LLC)*: This sub layer is bound to provide services for error control and managing frames. It presents the multiplexing methods which makes it possible for multiple sources to communicate over the same network.

Network Layer

This layer is responsible for optimized route discovery from the source to the destination. In multi-hop networks, this layer provides the key feature of finding best routes for packet transmission. This layer provides switching and routing capabilities in WSN. The main functionalities of Network layer include error packet sequencing, handling, addressing and sequence control. It also offers best Quality of Service (QoS) on Transport layer's request.

Transport Layer

This layer is responsible for providing acknowledgements for the successful data transmission, transparent data transfer and reliable data transport service to the application layer.

Application Layer

Application layer is the user interface and is responsible for handling, displaying data and images to the user in more human understandable format. It also takes care of managing traffic and providing software for application that translate the data in an recognizable form.

2.1.5 Duty Cycle Concept

Duty cycle is the measure of active time of a node. It is calculated as the ratio of listening interval to the total interval (listening and sleeping). A small duty cycle is implemented in order to mitigate the effects of idle listening, in which the node just wakes up to listen/transmit and then go back to sleep. It also avoids overhearing of unnecessary signals. Duty cycle can be set as per the application requirements. Low duty cycle can perform well for low rate networks but will fail tremendously for high rate data transfer. As per the applications, duty cycle can be tailored in order to achieve desired results like low latency, low energy consumption, etc.

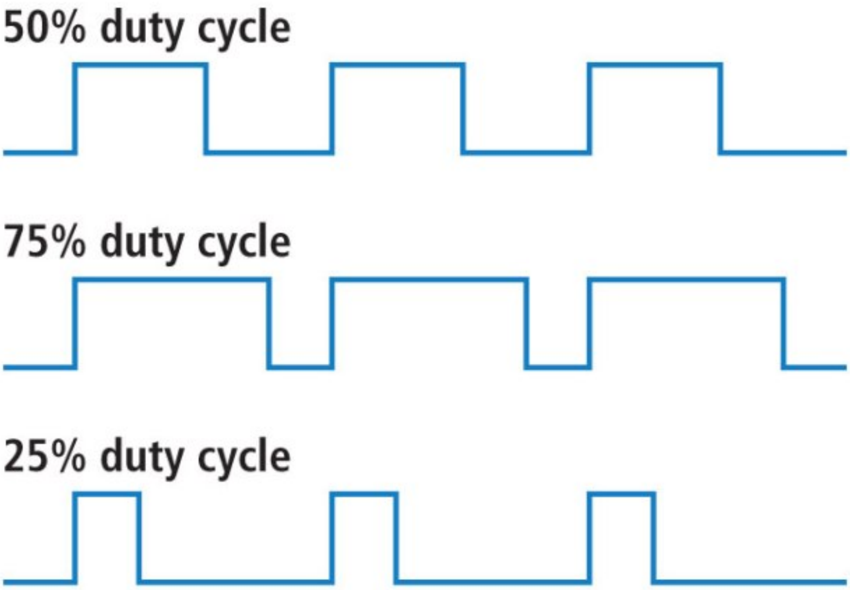


***Figure* 2.5** *Example depicting duty cycle [29]*

The whole idea behind low duty cycle protocol is to decrease idle listening and over hearing which is an energy waste. It can be avoided by putting the node to sleep mode when not in use. The most ideal operation is when the node wakes up only to transmit and receives packet and sleeps for the rest of the time. It is also known as periodic wake-up scheme. As shown is Figure 2.5, different duty cycles can be implemented for different applications.

There can be a situation where a sender node is transmitting but the receiver node is sleeping. Consider a situation where node A has data packet to transmit to node B. Due to low duty cycle operations, node A transmits at its schedule but node B was sleeping as per its individual duty cycle. If the application requires reliability of data, there must be some synchronization between the transmitter and the receiver. Low duty cycle protocols can be categorized depending on properties like required channels, synchronization, etc. Based on synchronization, the low duty cycle protocols can be categorized as Synchronous and Asynchronous schemes. Synchronous schemes will enable the nodes to know the duty cycles of other nodes beforehand for reliable transmission of packets. Generally, a node will have information about the small group of nodes around it and not the whole network (also known as global synchronization).

2.1.6 MAC Protocol in WSN

Idle listening and overhearing wastes huge amount of energy [30]. MAC protocols can enable low duty cycle operation in order to avoid idle listening and overhearing and to guarantee the long term sustainability of the network. Due to broadcast nature of wireless transmission medium, it is easily susceptible to interferences. Optimized and enhanced MAC protocols are required for proper interference control. There are two major types of access techniques: Reservation and Contention based approaches. Thus, all kind of MAC protocols are based on one or combination of above mentioned techniques.

1. *Reservation-Based Protocols*: Reservation based protocols ensures a separate slot for every node during which it can transmit/receive. This type of approach needs global information of the network to make a schedule, that allows each and every node to access the shared channel and communicate with other nodes. This approach can have various goals such as fairness among nodes, or reducing collisions. TDMA (Time Division Multiple Access)[5] is an example of such approach. In TDMA, time is divided into multiple frames and these frames are further subdivided into time slots. During a frame, each node has its own slot during which it can transmit the data. This helps in avoiding collisions. TDMA scheme provides with predictable latency and delays which help in designing an efficient routing protocol. The throughput, although can be large, still is limited, due to limited number of slots available. TDMA also ensures fairness among nodes as every node has its own slot. Although TDMA is quite appealing, it is coupled with some disadvantages like network topology dependency and time synchronization. Both global topology information and

dead-set time synchronization requires huge overheads and expensive hardware, thus making TDMA solutions less attractive in large scale WSN.

2. *Contention-Based Protocols*: Contention-based approaches are fairly simple when compared to the reservation-based approaches. It is because it neither needs topology knowledge nor it requires the global network information/synchronization. In contention-based approach, all network nodes contends for the shared wireless medium and only winners can access the channel at a particular time. Some canonical examples of contention-based approach are ALOHA and CSMA (Carrier Sense Multiple Access). For instance, in CSMA, if a node has a packet to transmit, it first senses the channel for possible running transmissions. If the channel is busy, it waits for a random time (therefore postponing transmission) and senses the channel again. If the node finds the channel free, it starts with the transmission of the packet. CSMA has no central entity controlling the nodes and each node is on its own. Hence, CSMA is more robust to node mobility and dynamicity.

   Although CSMA is quite successful for most of the applications, it suffers from some major drawbacks. When the traffic load increases, the throughput of the network degrades. Also, the distributive nature preclude them to get the same efficiency as that of reservation based protocols. At the price of global synchronization, reservation-based protocols outperform the contention-based protocols.

2.1.7 Routing Protocol in WSN

Routing protocols ensures the most optimal route for the packet transmission from source node to destination node. It can also ensure the fairness between the network nodes in terms of energy consumed for forwarding the packets. Using routing protocols, efficient data aggregation techniques can also be implemented before forwarding the packets. Routing algorithms can be classified into three groups[2]:

1. *Flat-based Routing*: In flat-based routing, all nodes are assigned the similar roles and cannot be changed. This is the most basic type of routing protocol. Flat routing protocol shares the routing information to nodes that are not already connected to each other in any way. In simpler words, these protocols don't perform under a pre-defined network layout.

2. *Hierarchical-based Routing*: In hierarchical routing, same node can play different roles in the network. A classic example of Hierarchical protocol is Low-energy adaptive clustering hierarchy (LEACH) [24] clustering protocol where all nodes are capable of being an active cluster members, as well as cluster heads. These kind of protocols are based on multiple level clustering where each cluster has its leader.

3. *Location-based Routing*: In location based routing, location of the nodes is used to create an optimum path for the packets to reach its destination reliably. This type of routing works fine for the static networks whose location is fixed. Some network uses a centralized control for determining the location and choosing an optimal path from source to destination while some network nodes contains Global Positioning System (GPS) on-board which can determine the node locations.

2.2 Energy Harvesting based Wireless Sensor Networks

2.2.1 Definition of Energy Harvesting Wireless Sensor networks

Energy harvesting is a method or process of deriving energy from the environment. Some examples of ambient energy sources are solar, thermal, wind, kinetic etc. The type of energy harvester is chosen as per the application location and needs. This ambient energy is captured and stored in small storage devices like supercapacitors or rechargeable batteries.

Energy-efficiency has been the focus of WSN research for a long time because nodes have been powered up by batteries. Once the node energy is depleted, the node is considered to be “dead”. Due to wireless sensor nodes locations, sometimes it is not possible to replace or recharge the battery. For e.g., nodes in or near a volcano [49] are dropped from an airplane and hence, are not humanly accessible. Hence, different methods have been proposed to slacken the battery depletion, which includes power control [16] and duty cycle based operation. The latter technique exploits the low power functioning of wireless transceivers, whose components can be switched off when not in use to save energy [6]. Adopting protocols with low duty cycle can enable the long lasting sensor networks. Although this approach increases network lifetime, if suffers from two major drawbacks:

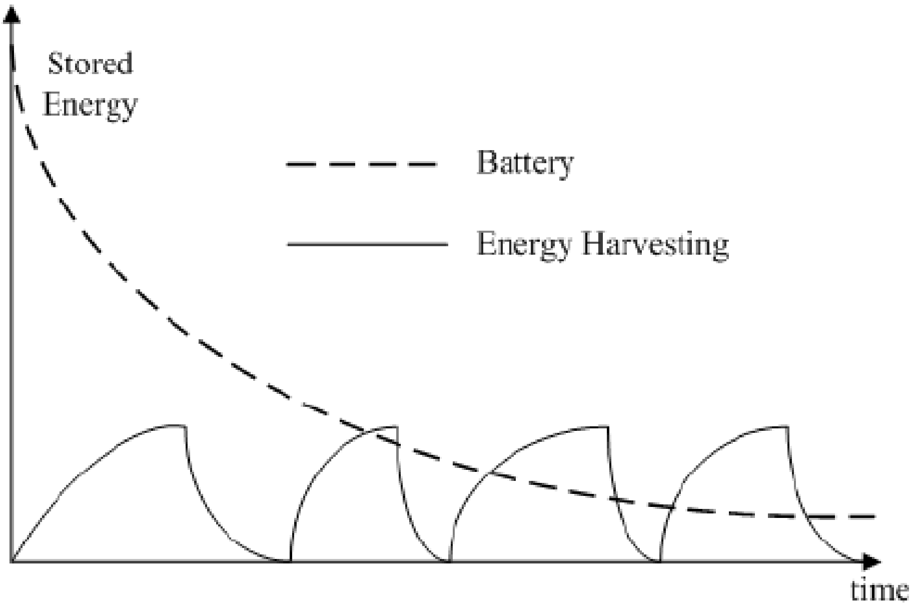


Figure 2.6 *EH-WSN versus battery-operated WSN [4]*

- Trade-off between energy efficiency and data latency.
- Battery still needs to be replaced at some point of time which is a problem for upcoming IoT applications.

Therefore, it is required to replace batteries with something which can sustain for a long period of time and is environmental friendly. Energy harvesters are considered to be one of the possible solutions. A sensor network enabled powered by harvesting ambient energy is known as energy-harvesting based Wireless Sensor Network (EH-WSN). In Figure 2.6, charging and discharging cycles of EH-WSN and traditional battery powered WSN is shown. It is obvious from the curve, that energy harvesting is an unpredictable operation and can scavenge a very low amount of energy. Latency is another issue as the storage needs time to charge (charging time) for proper operation of the network. On the other hand, when energy is harvested from the environment, we have access to unlimited power, and therefore we can have infinite lifetime of network. Using the term “infinite lifetime” means that the lifetime of sensor nodes is not restricted by the power supply. Hardware failure can still lead to a dead sensor node.

2.2.2 Energy Neutral Operation (ENO)

In order to achieve "infinite lifetime", a sensor node must operate in Energy Neutral Operation [28] state. The ENO concept refers to a state where energy consumed by a sensor node is always equal or less than energy harvested from the environment. Since the environmental energy source dynamics are unpredictable, it is difficult to design the sensors which adhere to ENO state. Some applications use regular batteries to compensate the network with enough energy.

However, using the normal batteries will void the concept of EH-WSN being environmental friendly. Vigorito et al. [48] defines the ENO-Max state where the node performs with maximum ability while still maintains the ENO state. ENO-Max state can be seen in Figure 2.7 which also shows a correlation between energy consumption and performance. ENO-Max is a state when energy harvested becomes exactly equal to the energy consumed by the node. Although it is the state of most optimized performance, it can never be achieved with harvesting ambient sources (due to its unpredictability). It is not possible to have a constant energy supply using harvesters.

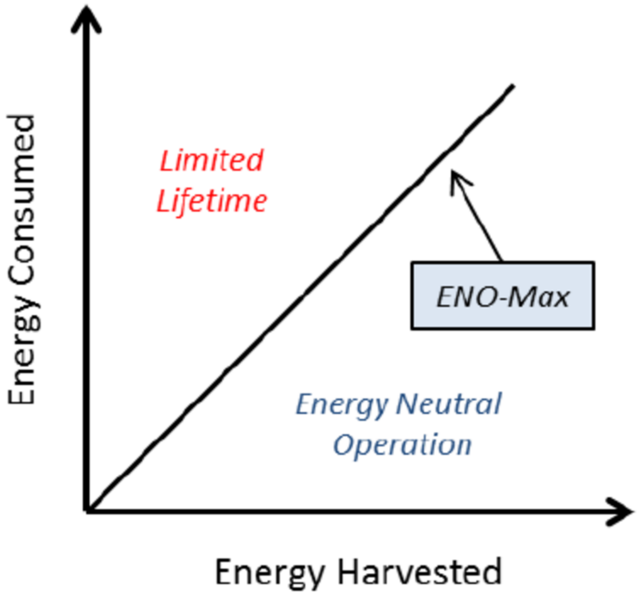


Figure 2.7 Energy Neutral Operation (ENO) state with ENO-Maximized performance (ENO-max)

2.2.3 Components of EH-WSN node

Small device size is the main requirement of upcoming IoT devices. EH-WSN are composed of such small sensor nodes that are capable of scavenging energy from nearby ambient sources and converting them into usable electrical energy. By using energy harvesters, WSN's will be able to operate for a theoretically infinite time until hardware failure. Each energy harvesting nodes typically comprises of one or more energy harvesters that convert ambient energy into electrical power, an energy storage device (e.g. supercapacitors) to store that harvested energy, a sensor for sensing a quantity, a microcontroller for processing the data and a transceiver for communications. The main difference between a traditional battery-powered wireless sensor node and EH-WSN node is shown in Figure 2.8 and 2.9.

The main component in EH-WSN is the energy module. The energy characteristics of an EH-WSN node are different from the traditional WSN as shown in 2.8 and 2.9.

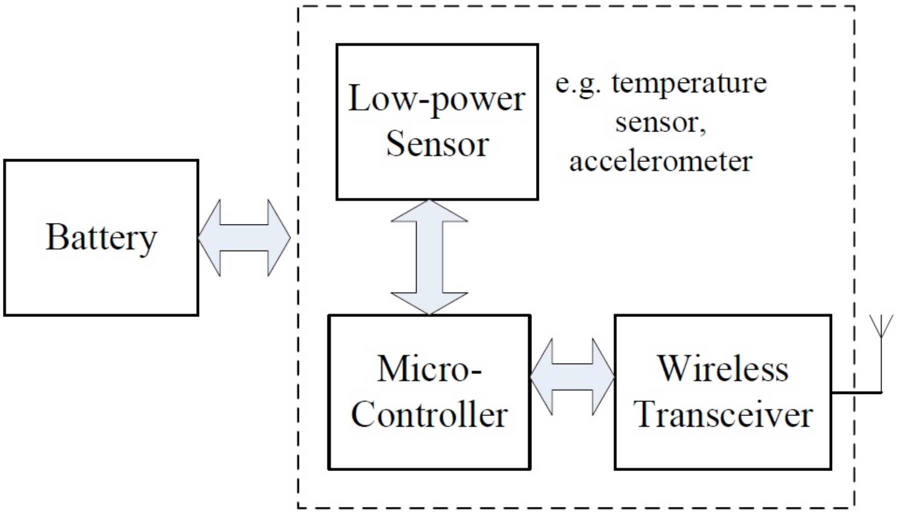


Figure 2.8 *Battery-Operated WSN node Energy Module [4]*

In traditional WSN node, the total energy decreases with time and the sensor node can ideally function until the energy reaches unusable level. But in EH-WSN, energy can be replenished using energy harvesters. Since the energy levels achieved using state-of-the-art harvesting devices are fairly low, harvested energy needs to be accumulated before it reaches the level of operation. Storage devices like supercapacitors offer theoretically unlimited recharge cycles and are environmental friendly.

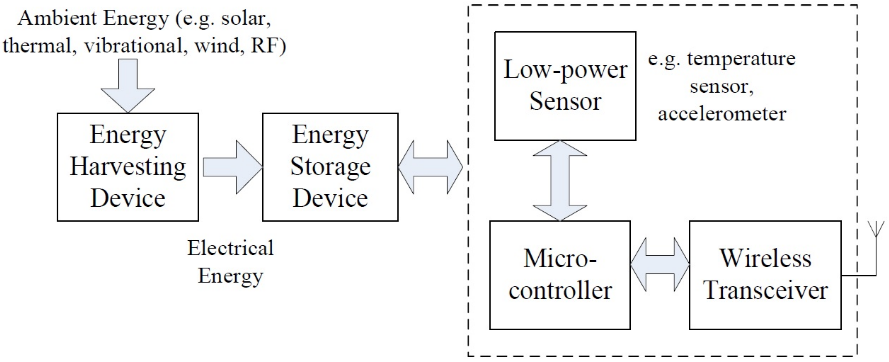


Figure 2.9 *EH-WSN node energy module[4]*

Power management module is responsible for efficient use of harvested energy. It is not necessary to store the harvested energy but it can be directly used for node operations. Power management module also minimizes the energy wastage in case of high energy harvesting rates. It takes care of managing the residual energy and putting it to efficient use. In Figures 2.8 and 2.9, a EH-WSN node is shown where battery is replaced with a combination of energy harvester and energy storage.

2.2.4 Energy harvesting techniques

Various energy sources are being considered for EH-WSN but a single energy harvesting source is not so efficient for all kinds of applications. For instance, solar harvesting can be useful in most of the outdoor applications but is not suitable for the indoor applications. It is important to make sure that the generated power is at suitable voltage and current levels for proper operation. EH sources are categorized as ambient and external sources.

Ambient Sources

Ambient sources are easily available in the surrounding at no additional costs. Some examples of ambient sources are Radio Frequency - Energy Harvesting (RF-EH), solar Harvesting, thermal Harvesting and wind Harvesting.

External Sources

External sources are intentional energy sources placed in the environment explicitly. For some applications like indoor positioning, ambient energy harvesting solely are not enough. Such application needs some intentional energy source which can provide the required power wirelessly. External sources are used in order to create an on-demand energy source which can provide energy in the time of need. A descriptive information on the available energy sources and harvesters is accumulated in [40]. A single sensor node can harvest energy from one or more harvesting sources. Some of the existing commercial energy harvesting based sensor nodes available like AdaptivEnergy, Enocean and Powercast. The amount of energy that can be harvested depends on the energy harvester's efficiency and size. Table 2.1 contains a summary of some energy harvesters and their power densities.

Table 2.1 *Harvesting rates for different types of energy harvesters [4]*

Type of Energy Harvesters	**Power Density**
Ambient RF	<10 $\mu W/cm^2$
Ambient light(Outdoor sunlight)	100 mW/cm^2
Ambient light(illuminated office)	100 $\mu W/cm^2$
Thermoelectric	60 $\mu W/cm^2$
Vibrational Micro-generators(machines)	800 $\mu W/cm^2$
Piezoelectric(finger motion)	2.1 mW
Vibrations(indoor environment)	0.20 mW/cm^2

2.2.5 Energy Storage techniques

The most common type of storage [20] in traditional WSNs are batteries as they are readily available and the discharge and energy characteristics are widely known. But these batteries come with its own disadvantages. Firstly, normal batteries cannot replenish their energy storage and needs to be replaced after depletion. It is impossible to replace or recharge the batteries in some of applications like volcano monitoring [31]. Once exhausted, disposing these batteries is a challenge and an environmental hazard. One eco-friendly option for energy storage is supercapacitor and can work as the primary energy storage. A supercapacitor in WSN can be recharged for infinite cycles (theoretically) and has a 10 year operational lifetime before the energy capacity is reduced to 80 percent [42].

3. ENERGY EFFICIENT AND ENERGY HARVESTING BASED MAC PROTOCOLS

3.1 T-MAC

The Timeout-MAC (T-MAC) [18] is the link layer protocol derived from S-MAC [50]. T-MAC was developed in order to curb the shortcomings of fixed duty cycle in S-MAC. Fixed duty cycles can be a problem for the applications with the variable loads. The main idea behind T-MAC is to send all buffered packets in burst of variable length, and to sleep in between the bursts to save energy. In order to maintain an ideal active time, its length should be determined dynamically. Figure 3.1 presents a very basic scheme of the T-MAC protocol.

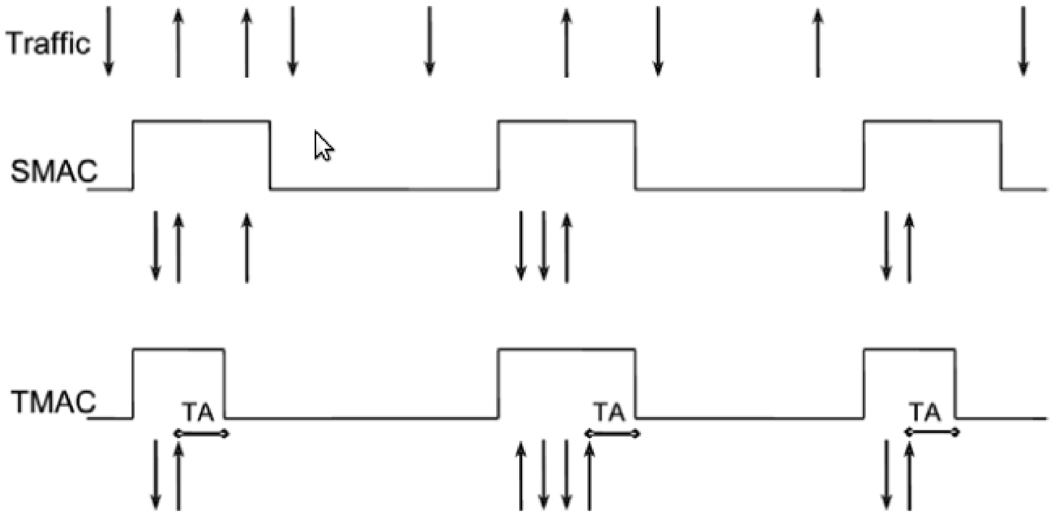


Figure 3.1 *Basic Scheme for T-MAC and S-MAC compared*

Each node wakes up periodically to communicate with its neighbors and goes back to sleep again until the next frame. In the meanwhile, new messages are queued up. Request to Send (RTS), Clear To Send (CTS) and Acknowledgement (ACK) are used for communication in T-MAC. The benefit of using the T-MAC protocol is its ability to have variable active time (as per the load). A node will continue listening or transmitting when it is in active period and it goes back to sleep when no activation event occurs for a time interval TA. An activation event can be any of the below mentioned events:

- periodic frame timer is fired
- received data packet at radio
- sensing ongoing communication at radio
- end of self data packet transmission or ACK
- the knowledge about neighbor's data transmission through RTS/CTS

If the node is not active, it can go to sleep. TA interval assures the minimum idle listening time in a frame. The TA time-out initiates all the communication at the start of the frame. As packets generated while sleeping will go to buffer, the capacity of buffer will determine the max frame period.

3.1.1 Cluster and Synchronization

After node start-up, it waits and listens to the channel. If no communication is heard during a random amount of time, it decides a frame schedule by its own and transmit a SYNC message which contains the schedule till start of next frame. During start-up, if a node hears a SYNC message from some other node, it will follow the same schedule as the received SYNC message and transmit its own SYNC subsequently. After small durations, all nodes transmit their SYNC again amd they also listen till the end of the frame scarcely, in order to check the presence of the other schedules nearby. This facilitates the new nodes to adapt and add to the current network. If a node already has a schedule and listens to another node with some other schedule, it has to adapt to both the schedules. Adapting to both schedules represents an activation event for the node, at initialization of both the frames. The above mentioned synchronization scheme is inspired by a concept called virtual clustering [50]. The virtual clustering forces the network nodes to form clusters with the nodes with same schedule, without necessitating the same schedule to all the other nodes in the network. It removes the need to keep the neighbor's information.

3.1.2 RTS operation and choosing TA

In IEEE 802.11 [14] contention based protocols, nodes wait for a random time within a contention interval after detecting a collision, usually using a back-off scheme. The contention interval increases when traffic increases because the back-off scheme reduces the probability of collisions when the load is high.

In T-MAC, each node transmits its buffered messages altogether at the frame's beginning. During this burst, messages are transmitted at the maximum rate possible. The network load is mostly high in the beginning of the frame and that is why, changing the contention interval is not so helpful. Therefore, RTS packet transmission in T-MAC begins by wait-and-listen for some random time within the contention interval and this interval is tuned for the maximum load possible. This contention time is even used in case of no collision.

3.1.3 RTS Retries

When a node transmit a RTS packet, but doesn't receive a CTS packet in return, one of the three cases might have occurred; (i)receiver didn't hear the RTS, due to collision; or (ii)receiver node is prohibited from replying due to an overhead RTS/CTS; or (iii)the receiver is sleeping. When a sender node receives no answer within the interval TA, it might go to sleep. Since this can happen in the beginning of the frame, the throughput would decrease. Therefore, a node must retry the RTS if it doesn't receive an answer. If there is no answer after a certain retries, the sender can go to sleep.

3.1.4 Determining TA

Choosing TA is the most important part of this protocol as it can extend or shrink the active time (duty cycle, eventually) of a node based on the traffic situation. A node should stay awake while its neighbors are transmitting. Receiving the start of RTS or CTS packet from a neighbor is enough to trigger a renewed TA interval. Due to short transmission range, a node might not hear the RTS packet that initiates a communication with its neighboring nodes. Therefore, TA interval must be long enough to receive at least the start of the CTS packet (as in Figure 3.2). Using this, the lower bound of TA interval length is calculated as:

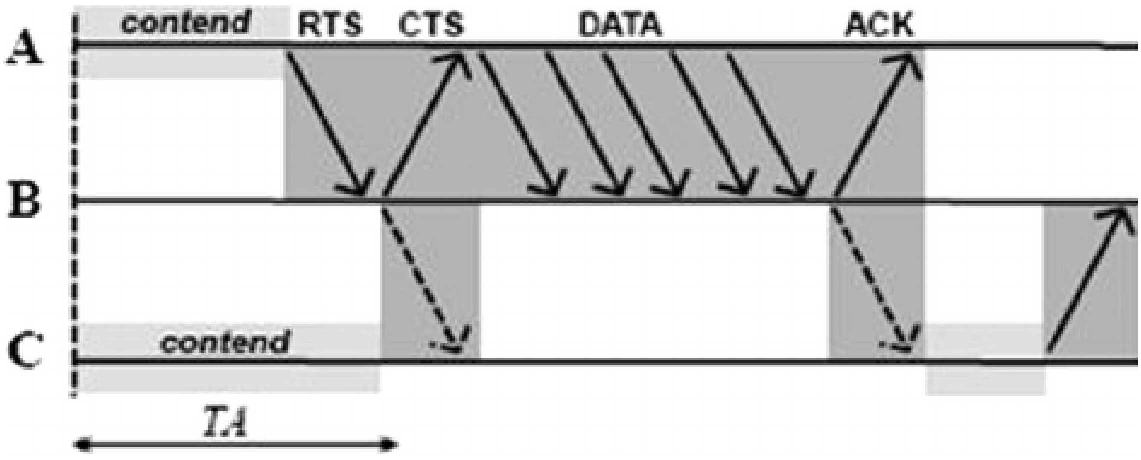


Figure 3.2 *Basic data exchange in T-MAC [1]*

$$TA = C + R + T$$

Where C is length of the contention interval, R is the length of RTS packet and T is turnaround time i.e. time between end of RTS and start of CTS packet. Increasing the TA eventually increases the energy used. T-MAC has largely suppressed the shortcomings of S-MAC protocol with the variable duty cycle concept. On one hand, T-MAC does provide with a low energy communication while on the other hand, has low maximum data throughput.

3.1.5 Advantages and Disadvantages

The Timeout Scheme of T-MAC protocol minimizes the energy usage by idle listening when compared with S-MAC. This enables nodes to have variable duty cycle as per the network load or buffer size. It is suitable for environments with varying message rate. Hence, it will work efficiently for energy harvesting based networks as EH-WSN nodes normally harvest energy for a while and buffer packets as per the packet generation rate. Energy harvesting based nodes can contain one or multiple packets in its buffer, and thus needs variable duty cycle. The collision detections, retransmission, RTS/CTS schemes are other benefits which avoids problems like hidden node terminal. A disadvantage with T-MAC is the problem of early sleeping which leads to packet loss.

3.2 On Demand Medium Access Protocol (ODMAC)

The main feature of ODMAC (On Demand Medium Access Protocol) protocol [21] is to allow the nodes to choose their individual duty cycle and adjust it according to different parameters like harvesting rate. This feature leads to the trade-off between power and performance. For instance, if a node contains power in abundance, it can increase its duty cycle in order to send as many packets as it can, with the available power. On the other hand, nodes with less power can decrease their duty cycles and harvest more power meanwhile. Hence, adjusting the duty cycle will affect the throughput and delay related to the network.

ODMAC is based on Receiver-Initiated [22] paradigm which shifts the idle listening time from receiver to transmitter. Every ODMAC based receiver broadcast a beacon periodically which is a signal for transmitters to send the data packets.

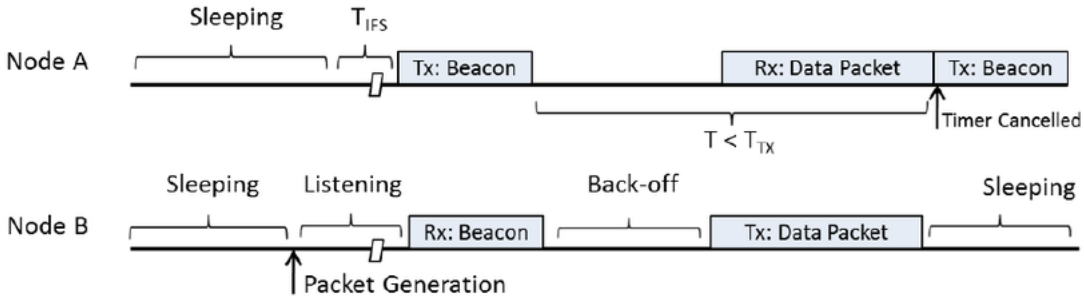


***Figure* 3.3** *Communication between ODMAC transmitter and an ODMAC Receiver*

All the nodes that have queued packets to transmit are listening to the channel, waiting for an appropriate beacon. Once the beacon is received, data transmission starts. This eliminates the idle listening of the receiver which has no idea on when the data will be transmitted from the transmitter but in ODMAC, the receiver just spends energy on periodically broadcasting a tiny beacon frame. Even though the energy wastage in idle listening is shifted to transmitter, it is trivial in low traffic conditions.

Figure 3.3 shows a basic communication between a transmitter and a receiver in ODMAC. Let us assume node B is transmitting and node A is receiving. Node B first listens to the channel for arriving beacon. At some point when node A has a packet to transmit and enough energy for transmitting, it attempts to transmit a beacon informing its availability. Firstly, node A listens to the channel for time

(T_{IFS}). If the channel is busy through that time, node A goes back to sleep and tries again after some time. And if the channel is not busy, beacon is transmitted by node A and initiates a waiting timer, T_{TX}, and waits for an incoming packet. If no packet is received by node A in time T_{TX}, node A goes to sleep state. If the beacon is received by node B, it will identify the source and start transmitting data packets to node A. Before transmission, node B waits for a random time slots, T_{SLOT}, in the interval defined by the contention window (CW), i.e. $[0, CW - 1]$. If the channel is busy, node A then drops this beacon and starts listening for the next beacon and if the channel is not busy, the node starts with data transmission. Once this data transmission is over, node B goes back to sleep state. If it has queued up packets to send, it continues to listen for the beacons. In order to save energy of the transmitter in idle listening, node A never goes into the sleeping state, and immediately transmit another beacon. It helps the transmitters with multiple queued packets and to resolve the contention issues.

3.2.1 Duty Cycles

The main metric in ODMAC is *end-to-end delay* and energy conservation. The beacon period, T_{DC}, is the node's individual duty cycle for performing forwarding task. This period can be adjusted in order to achieve a particular end-to-end delay or the consumed energy depending on the application. This feature is the trade-off between energy consumption and end-to-end delay. When beacon period is low, more beacons are transmitted and higher energy is consumed. On the other hand, for higher beacon period, the energy consumed is decreased as less number of beacons are transmitted in a particular period of time. If case of high duty cycle period, the packet might be sent through a different path and it can help the node to save energy but will also introduce large end-to-end delay. Another important metric for performance is the sensing rate. The sensing period defines the sensing task's duty cycle. The high sensing rate means more energy consumption, high generation of packets and therefore, more forwarding tasks for the node. Hence, the administrator is forced to choose between the performance metrics (due to trade-off).

ODMAC provides two operating modes namely *static and dynamic* duty cycle modes. In static mode, the sensing period and the beacon period of each node is explicitly fixed by the admin of the network. In this case, ODMAC will not be able to guarantee ENO [28] state. While in dynamic mode, ODMAC adjusts the two duty cycles in order to reach the state of ENO-Max. ODMAC gives the control of performance metrics to the administrator. The admin can choose between sensing period, energy consumed, relaying tasks or the duty cycles. For duty cycle algorithm, a very complicated algorithm is used. A more mature dynamic duty cycle algorithm [34] [48] can be used in case of better performance requirements.

3.2.2 Opportunistic Forwarding

In ODMAC, if the receiver is set on high duty cycle period, the TX will be waiting for long period to transmit a packet, thus wasting precious energy and boosting end-to-end delay. Developers of ODMAC tried to solve this problem using "Opportunistic Routing or Opportunistic Forwarding Scheme". Every node carries a list of potential forwarders which are eligible candidates to be the receiver and will be comparatively closer to sink than that of transmitter. Instead of waiting for a beacon from some specific node, the ODMAC just transfers the packet to the first received beacon, as far as it is in the list of potential receivers. This will certainly reduce the waiting time for nodes to forward the packet and at the same time, enables the control of packet relaying node-distribution in the network. Node with higher beacon period will be forwarding less number of packets than the node with lower beacon period. Hence, the nodes with high energy harvesting rate can help to compensate for the nodes with low harvesting rate.

3.2.3 Advantages and Disadvantages

Although, ODMAC is proved to be eligible for energy harvesting capable network nodes, it needs to be modified as per the application. ODMAC doesn't offer acknowledgement and retransmission options and hence, upper layers should be responsible for handling collisions. It also contains the popular *Hidden-node problem* which is normally handled by RTS/CTS function of a protocol. Even with these shortcoming, ODMAC performs well for many network scenarios. ODMAC protocol is receiver-initiated which doesn't transmit until receiver asks for it. It nearly eliminates the idle listening time of the receiver, thus saving a lot of energy. At the same time, it also maintains the communication supporting individual duty cycle. This protocol also allows the administrator to change the protocol configuration as required by the application. Finally, ODMAC provides the opportunistic forwarding scheme which mitigates the end-to-end delay and also distributes the traffic load around network.

3.3 DeepSleep: IEEE 802.11 Enhancement

Machine-to-Machine (M2M) communications refers to communications between devices without manual assistance. As MAC protocol design for M2M communications is very similar to that for WSN, most of the proposed MACs are applicable to both of the technologies.

The DeepSleep [32] scheme is designed in order to support the network of energy-harvesting enabled devices. The aim of DeepSleep is to increase energy-efficiency and mitigate packet loss rate, outage probability and delay time. The major target is to eliminate or at least decrease the effects of overhearing which leads to huge energy waste and to make channel contention level less severe. This DeepSleep scheme is an enhancement on 802.11 baseline scheme for energy harvesting applications. Basically, it is an enhancement of IEEE 802.11 Power Saving Mode (PSM). DeepSleep scheme is divided into two schemes.

3.3.1 High Priority Energy-Aware Sleeping

In this initial step, the value of Minimum Contention Window (CW_{min}) in IEEE 802.11 backoff procedure is focussed. This period (CW_{min}) can influence the over hearing (and idle listening) duration and overall collision probability. If some sensor nodes are deliberately allocated with small (CW_{min}) for packet transmissions, they will have higher priority than others, which will mitigate the idle listening. But at the same time, if too many nodes are allocated the lower (CW_{min}) simultaneously, then it will increase the contention level, which will lead to large number of collisions and hence, many retransmissions will degrade the energy efficiency. Thus, devices with less residual energy are given higher channel access priority after sleeping for a while, to drop out channel access. Now for being energy aware, the node constantly checks its own battery level i.e. E. If the value of E goes below $E_{DeepSleep}$, a threshold higher than usable energy level E_O, then node goes to sleep to harvest some energy and marking *HighPriority* Boolean ((a Boolean to keep track of priority)) as true. For being high priority packet algorithm, when node has packet to transmit, it wakes up and checks for *HighPriority* Boolean, if it is true, the node will set its CW_{min} a lesser value $CW_{DeepSleep}$ and again set the *HighPriority* Boolean as false. Or the node will set its own CW_{min} to default $CW_{minOriginal}$.

3.3.2 Random Deferring

In IEEE 802.11 baseline scheme, if nodes has packets in buffer, nodes will wake up simultaneously and will try to send packets from the start of beacon period. This packet transmission process consists of idle-listening for a while, overhearing and then data transmissions and Acknowledgement (ACK) reception. As the number of nodes in the network increases, the contention level increases which leads to lengthened overhearing and idle-listening time through the back-off procedure. It is normal that most of the devices will stay awake till their buffers are empty. If the wake-up schedules for some nodes can be delayed, the overall wasted energy in back-off procedure can be decreased. Also, the channel contention level will also decrease due to decreased number of nodes contending simultaneously. Using Random Deferring, Access point (AP) or sink broadcasts the beacon frames which contains sleeping probability $P_{DeepSleep}$ and the deferring time as $T_{DeepSleep}$ to all network nodes. Node will wake up to transmit the packets after receiving beacon frame and will decide if it should go to sleep or not as per the $P_{DeepSleep}$. Once the node sleeps, it will wake up after the time $T_{DeepSleep}$.

3.3.3 Advantages and Disadvantages

The main advantage of using DeepSleep scheme is the reduction of number of active nodes leaving low contention level. This decreases collisions, idle listening and overhearing. DeepSleep also provides fairness among nodes in terms of energy and packet transmission. Devices with lower harvested energy also gets an edge over the transmission medium by assigning higher priorities to such nodes. Apart of mentioned benefits, DeepSleep lacks in multiple fields. In controlled access, all nodes have same sleeping probability, which indicates that the ones just woke up from a DeepSleep might go back to sleep again. This protocol assigns them higher priority of transmission channel, but they still have to get permission for staying awake for transmission. These successive DeepSleep events may lead to increased delay. Another limitation of DeepSleep scheme is Single hop network operation.

4. ENERGY EFFICIENT AND ENERGY HARVESTING BASED ROUTING PROTOCOLS

4.1 LEACH

Low Energy Adaptive Clustering Hierarchy (LEACH) [24] is a TDMA based routing protocol [13]. The purpose of this protocol is to improve the overall lifetime of WSNs by decreasing the energy consumed. In LEACH, the nodes organize themselves into clusters and a node among them is chosen as the local BS or cluster head (CH). A cluster contains a cluster head and one or more cluster members. For normal WSN operation, all the nodes were interacting with the sink directly and therefore spending energy based on their distance from the sink. But in LEACH, all cluster members send their data to their cluster heads and cluster head sends it to the sink. In addition, LEACH also performs local data fusion [51] in order to compress the amount of data being sent from the clusters to the BS which reduces energy dissipation and enhances the lifetime of the system. A typical WSN with clustering is shown in Figure 4.1.

Sensor nodes elect themselves to be a CH at any given time with a certain probability. These CHs will broadcast their status (of being the CH) to other nodes in sensor network. Using this broadcast message, sensor node will determine to which cluster it wants to belong, by choosing the CH which requires minimum communication energy or larger Received Signal Strength Indicator (RSSI). Once the network is arranged in clusters, the CHs will create a TDMA schedule for the nodes which belong to its cluster. This will have less interference from the nearby nodes as each node will have its own time slot for transmitting data. Next step for CH is to collect the data from the nodes in it's cluster, aggregate the data and then transmit the compressed data to the sink or base station.

CH is responsible for collecting, aggregating and transmitting the aggregated data to the sink. Therefore, being a CH is an energy consuming task and will drain

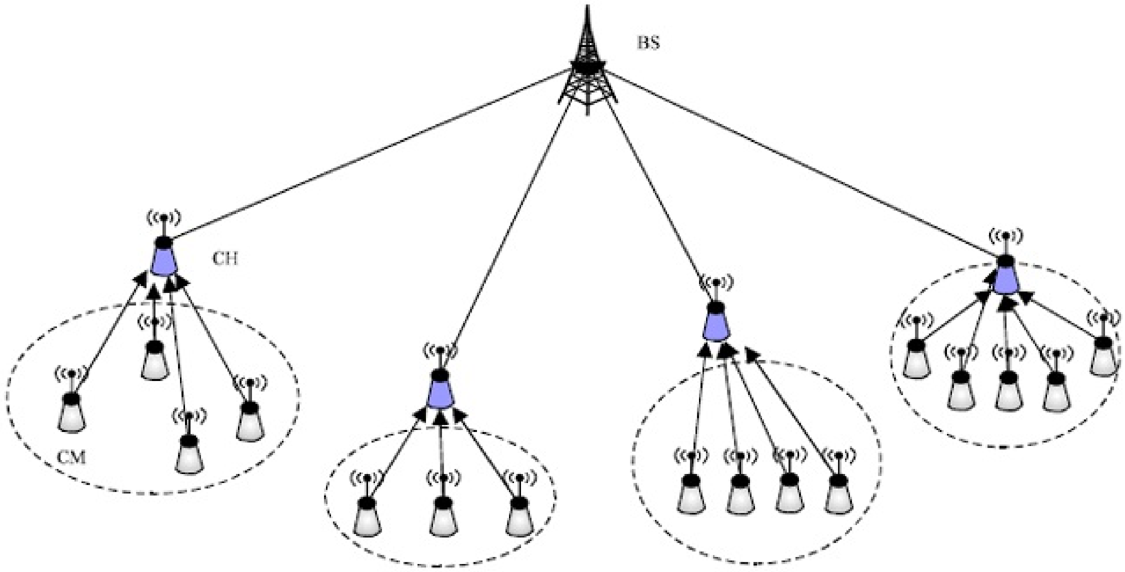


Figure 4.1 *Example of Network Clustering*

its energy at a faster pace. It is necessary to have some fairness in selecting the cluster head as a single node cannot handle the task of CH. In order to spread this energy usage over multiple nodes, the CH nodes are not fixed, and rather CH is selected at different time intervals. The decision to become a CH depends on a random probability or the amount of energy left in the node. In this way, the nodes with higher remaining energy will perform the energy-intensive functions of the sensor network. This decision of being a CH is taken by the node itself, so no extra overhead is needed in the selection process.

The LEACH operation is broken up in multiple rounds where each round contains two phases: Set-up phase when the clusters are organized and CH are selected; and steady-state phase when data is transferred to the sink. The steady-state phase in particularly longer when compared to the set-up phase in order to minimize the overhead. It contains a number of frames with individual time slots for every node that belongs to that cluster. An example timing diagram of LEACH operation is shown in Figure 4.2.

4.1.1 Set-up Phase

Set-up phase of LEACH, as mentioned before, is an initial setup for constructing a cluster and choosing a CH. This phase consists of three steps:

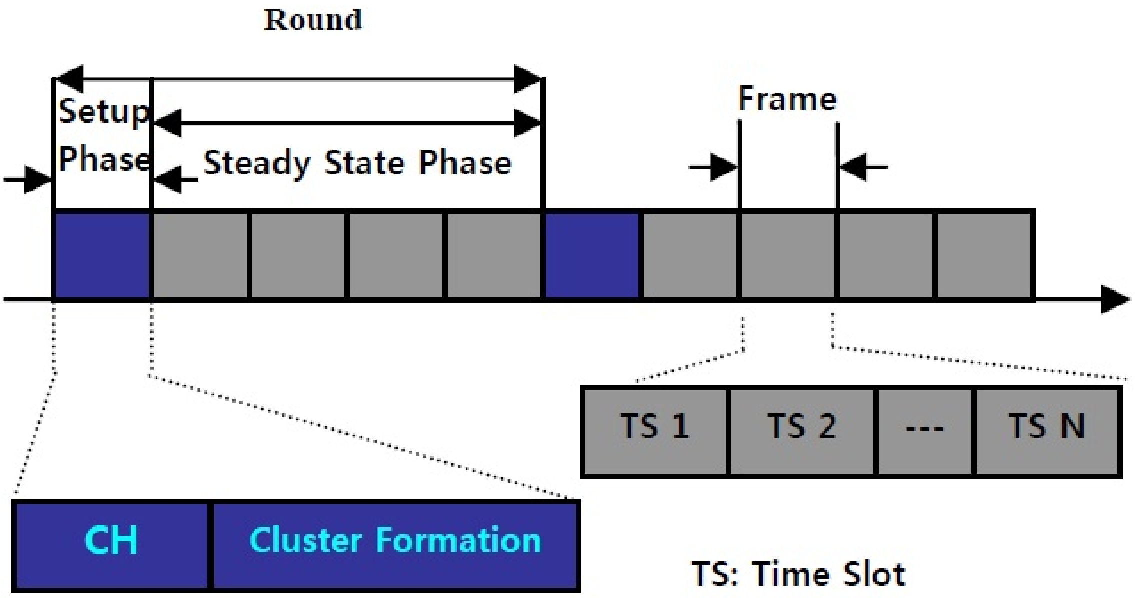


Figure 4.2 *LEACH operation timing diagram*

1. *Cluster-Head Advertisement*: In the initial phase when clusters are created, each node have to decide on becoming the CH for that round. This decision takes into account *the suggested percentage of CHs for the whole network (percentage of nodes of network acting as CHs) and the number of times the node has been a CH so far.* The node x chooses a random number between 0 and 1. If this number is less than the below mentioned Threshold T(n), the node becomes the CH for the current round. The threshold T(n) can be given as:

$$T(n) = \begin{cases} \frac{p}{1-p\times(r \bmod(\frac{1}{p}))}, & \text{if } x \in A \\ 0, & \text{otherwise} \end{cases}$$

Where p is the desired percentage of CHs, r is current round number and A is the set of nodes in the given network which have not been a CH in the last $\frac{1}{p}$ round. Utilizing this threshold, each node is going to be a CH at some point in $\frac{1}{p}$ rounds. If a node has already been a CH before, its probability of being a CH again will decrease and vice versa. After $\frac{1}{p}$ rounds, all nodes are once again equally eligible to become CH. In this version of LEACH, it was assumed that all nodes start with the same amount of energy and that being a CH will remove same amount of energy for each node. The CH elections can also be done considering the current energy of the nodes but this will require a certain amount of synchronization which can lead to latency and overhead packets. It is also assumed that all nodes are capable of reaching the sink in a single hop.

Once a node elects itself to be cluster head, it advertises itself to rest of the nodes in the network. For this, the CH sends a small packet (ADV Advertisement Packet using CSMA/CA MAC) containing the node ID to inform other nodes. All CHs transmits their ADV packet using the same transmit energy. In this phase, only the CHs are transmitting while the rest of the nodes are in receiving mode in order to head the ADV from the CH. Once the other nodes receive these ADV packet, they will have a list of CHs from whom they received the ADV packet.The nodes can make a decision on which cluster (or CH) they want to join and this decision can be made based on the RSSI of the received signal.

2. *Cluster Setup*: A cluster will contain one Cluster Head and one or more Cluster members. Based on the RSSI of the received ADV packets from multiple CH, cluster members (non-CH) choose the one with the highest RSSI and sends a JOIN packet. This JOIN packet informs the cluster head about which nodes belongs to which clusters. JOIN packets are unicast and are sent specifically to the CH with highest RSSI. A single CH will receive one or multiple JOIN requests. It will make a list of all the JOIN requests received and the cluster will be complete.

3. *TDMA Schedule Creation*: Once the clusters are created, each of the chosen CH creates a transmission TDMA schedule for its cluster members and then broadcast this schedule to its members. The number of created slots will be equal to the number of members in the cluster. By the end of schedule creation, each node will have its own time slot to transmit its packet to CH and hence, there will be no interference from the nearly nodes. Each node can transmit its data in the allocated time slot.

4.1.2 Steady-State Phase

It is assumed that all nodes have data to send and they will send it during their allocated transmission slot to the CH. This transmission will use the least possible amount of energy(as cluster were chosen based on RSSI or the closest one). The radio of each cluster node can be turned ON/OFF as required in order to minimize the energy dissipation in these nodes. The cluster head node must keep its radio ON during the transmission slots of its cluster member. When all the data is received by the CH, it performs signal processing or data aggregation function in order to minimize the data transmission to the sink node or energy usage for the same.

All cluster members transmit data to their CH in steady state phase. After a certain time, which is determined beforehand, the next round of operation begins where each node determines if it should be a CH for this round and advertising this information to the rest of the network.

4.1.3 Advantage and Disadvantages

Advantages

- *Energy-Efficient*: LEACH reduces the communication energy by eight times[24] as compared to the direct transmissions, therefore, increasing the lifetime of the network.
- *Data Aggregation*: A certain data aggregation and signal processing methods can help in energy conservation and traffic reduction in WSN.
- *No Centralized Control*: As this protocol is completely distributed, it needs no control information from the base station as well as no global network knowledge is needed.

Disadvantages

- *Number of cluster heads*: LEACH does not give any information on the number of cluster heads in the network and has to be set manually. If a CH dies, the whole cluster will die which will result in a huge loss of data.
- *Not suitable for EH-WSN*: In LEACH, it is assumed that all nodes contains same amount of energy which allows the random CH allocation. This leads to fairness among the nodes in a network. Due to unpredictability of the harvested energy, the random allocation of CH will not be feasible for the EH-WSN. A comparatively better option will be to choose the CH based on the residual energy. This will require a prior knowledge of the network and the control should be centralized, as mentioned in LEACH-C [24]. This may

also lead to increased start-up energy and not every node will get a chance to be a CH.

4.2 Multipath Rings Routing

Tree based routing schemes uses a single propagation path from the sensor nodes to the sink. But such schemes are highly susceptible to failures in data transmissions. Multipath Rings (MPR) routing is a multipath, multi-hop and diffusion based routing scheme for WSNs. MPR allows multiple paths for data transmission between sensor node and the sink. The data transmission will be successful as far as any one of the available paths is reliable.

The MPR protocol is based on diffusion technique as mentioned in [33]. In clustering, the energy dissipation is decreased by sending the data to the nearby node instead of sending it directly to the sink. But in MPR, there is no cluster head and hence, the data is sent to all the neighbors towards to sink. Firstly, the whole network is divided into rings i.e. each node will be given a ring number which will indicate its position with respect to sink. Ring number is the hop-distance from the sink. There can be one or multiple nodes in a ring. When a node have data to transmit, it will send it to the ring number lower than the its own ring number and will keep forwarding till it reaches sink [47]. MPR Routing protocol requires network initialization before transmitting data packets but no route discovery is necessary for the proper functioning of this protocol. An example network setup is shown in Figure 4.3 [35]. The operation of the multipath ring routing majorly consists of two phases as explained in the following:

4.2.1 Topology Setup Phase

The first step in MPR routing is to set up the sensor nodes network as per their distance from the sink. In other words, the nodes will be assigned to a particular group called Ring Numbers which defines the hop distance of a node from the sink. After this phase, every node will belong to a ring i.e. the number of hops from the sink.

In Topology Setup phase, a topology setup packet, as shown in Figure 4.4, is broadcasted by the sink with ring number equal to Zero. As mentioned earlier, ring number is the hop distance from the sink and therefore, sink is assigned as ring zero.

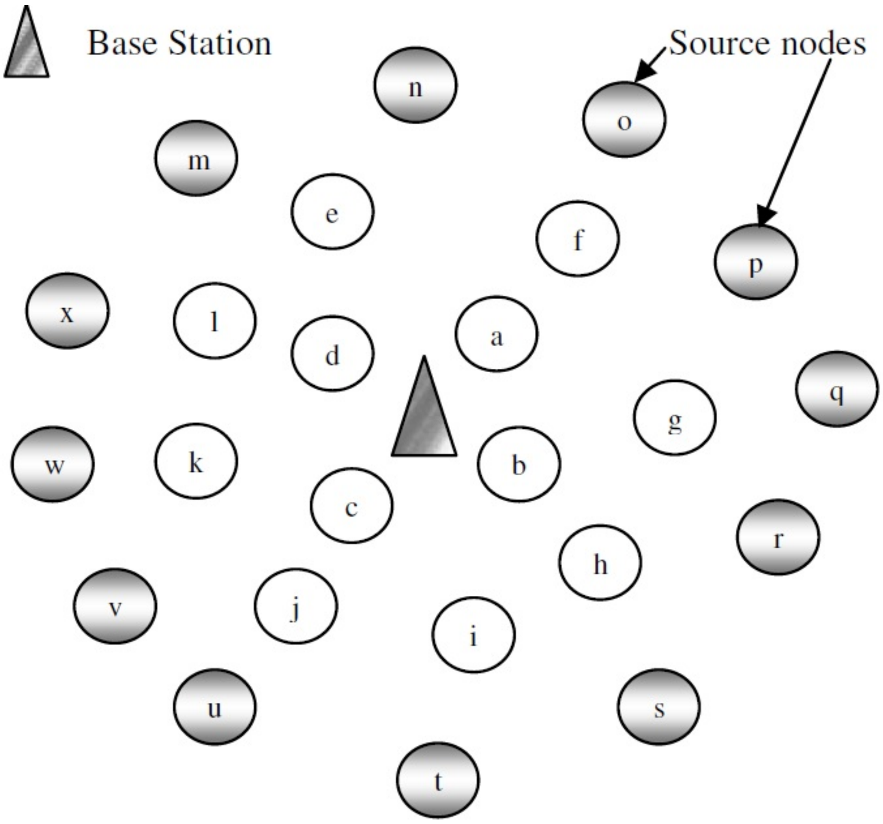
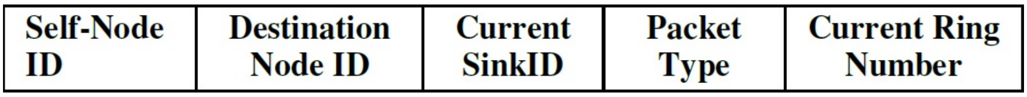


Figure 4.3 *An example network of sensor nodes with identification letters*

Sensor nodes in close proximity (neighbors) of the Sink will receive this packet. The receiver will increment the ring no. of received packet by 1, initializes its own ring number with the value ($received + 1$) and re-broadcast the packet to the network. For instance, all neighbors of the sink node will have ring number 1, and neighbors of nodes in Ring 1 will belong to ring number 2 and so on. Generally, if a node is at n-hop distance from the sink, it will belong to ring n.



Self-Node ID	Destination Node ID	Current SinkID	Packet Type	Current Ring Number

Figure 4.4 *Topology Setup Packet Format*

The Topology setup packet [25] contains 5 fields. Self-node ID and Destination node ID are self-explanatory as source and destination of the packet. Current Sink ID is used when network contains more than one Sink node. Packet type defines the characteristic of the packet i.e. topology setup packet in this case. The most important field for this routing operation is current ring number which is set to zero by the sink and incremented with every re-broadcast. Nodes will rebroadcast it only when the received packet ring number is greater than the current ring number (self-ring number). The complete procedure of setting up the ring numbers is described using a flow diagram in Figure 4.5. This process will continue till all nodes have their own ring number (or hop distance from the sink). Initially, nodes will contain ring number equal to ∞ but it will be modified to a real number by the end of the topology setup phase. A sensor node re-broadcasts the received packet only when self-ring number is greater than the packet ring number. Otherwise the packet will be discarded. This will avoid the transmission loops of packet and the unnecessary energy dissipation. Figure 4.6 shows an example network after the topology setup phase with assigned ring numbers as R1, R2 and R3.

Scalability is also a trait in MPR routing as new nodes can join the network at any point of time by sending a join network request. Upon receiving this request, the current members of network can send their own ring number to the sender node. Once the new node receives the ring number of its neighbors, it can set its own ring number to $PacketRingNumber + 1$. The nodes need not to have any information about their neighbors and all they need is their own ring number. That is why, all the packet transmissions are of broadcast nature and there is no unicast transmission in MPR Routing. Multiple energy-aware routing protocols, which normally aims on calculating least energy cost paths [39] [44], MPR routing protocol instead attempts to adopt all possible energy sufficient paths.

4.2.2 Data Dissemination Phase

Once the topology setup phase is over, all nodes will belong to a ring number which is their distance from the Sink. In most WSN cases, the network nodes have no global network information, so a sensor node will be unaware of the other nodes in the network. In MPR Routing, when a sensor node has a data to send, it won't send it to the destination node directly, but in fact will broadcast it with its current ring number or level. The nearby nodes will receive this packet and will check the received packet's ring number with their own. If this ring number is less than the received packet's ring number, the node will re-broadcast it after modifying the packet's ring number to its own (current ring number). Packet's ring number will be decreased by 1 with every re-broadcast till it reaches the Sink. The idea behind

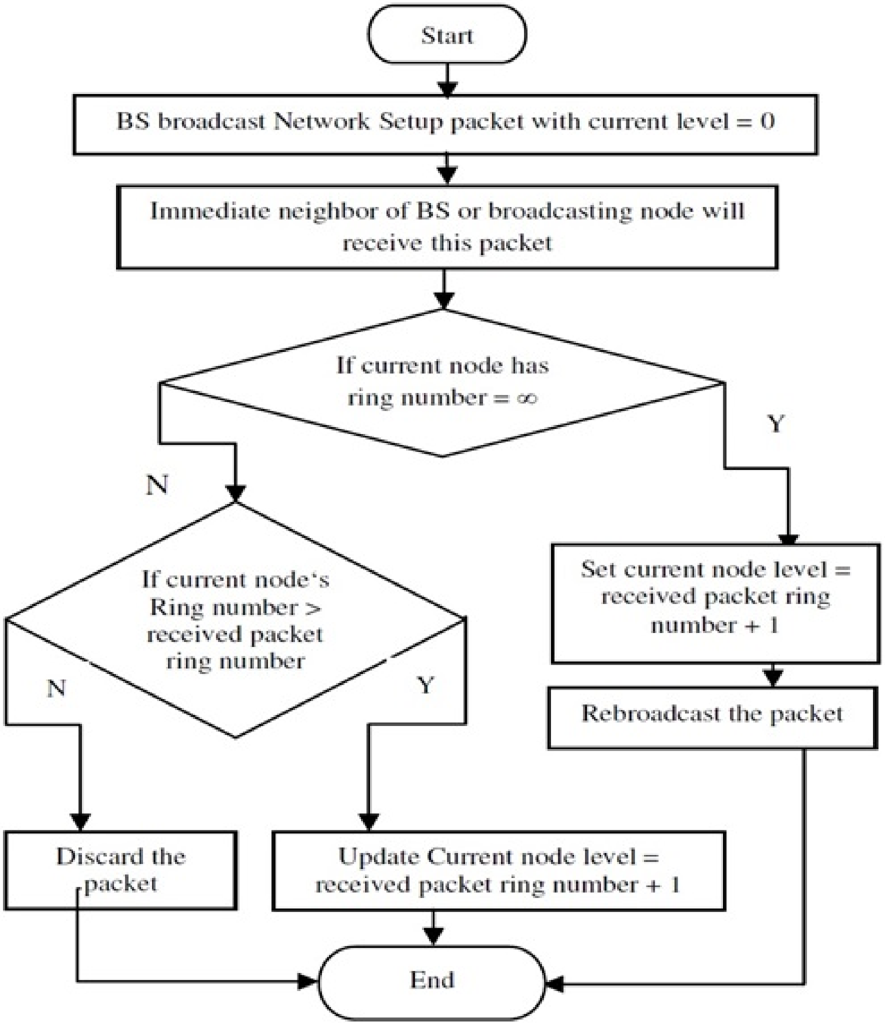


Figure 4.5 *Flow Diagram of Topology Setup Phase*

assigning the ring numbers to nodes is that with every re-broadcast, the packet moves towards the Sink and is ignored by the nodes with higher ring number.

Figure 4.7 shows the flow diagram to describe a typical operation of data dissemination phase. In this phase, when a node has data to send, it will broadcast it with its current ring number. Neighbors of the source node will hear the packet and check for its ring number. If it is lower than own ring number, that means the packet is coming from lower level and should be discarded. If it is higher than own ring number, it should be re-broadcasted after decreasing the packet's ring number by 1. Let us explain this operation with the help of an example: In figure 4.6, a simple WSN is shown after the topology setup phase with nodes belonging to Rings R1,

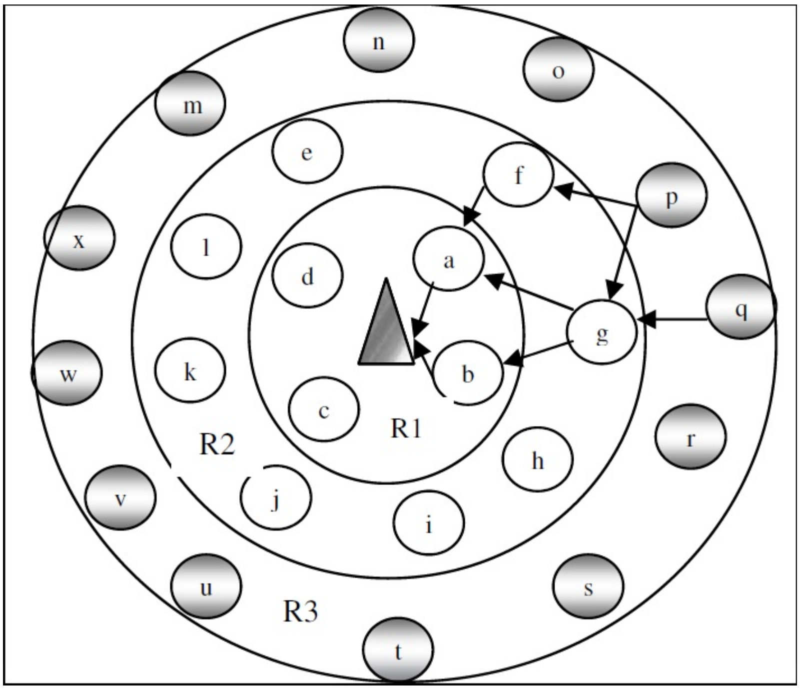


Figure 4.6 *Rings assigned after Topology Setup Phase*

R2 and R3. Assume that node p and node q (in Ring R3) have data to send to the sink. To do so, they will broadcast their data along with their Ring number i.e. 3 to the network. All the neighbor nodes will receive this data packet. Once received, receiver will compare its own ring number with the received packet's ring number. If received packet's ring number is higher than its own ring number, then receiving node will decrease the ring number of the packet by 1, and re-broadcast the packet. Otherwise the receiver will discard the packet. This condition ensures that with every transmission or rebroadcast, the packet is following the path towards the sink and not further away from it.

4.2.3 Advantages and Disadvantages

Advantages

- *Multipath*: Multipath property of this protocol gives the ability of being prone to route failure, thus making the network more robust.
- *Multihop*: Nodes transmit their data packets to the nearest neighbor towards sink with every hop, thereby saving energy. Sending the packets directly to the sink can be an energy consuming task.

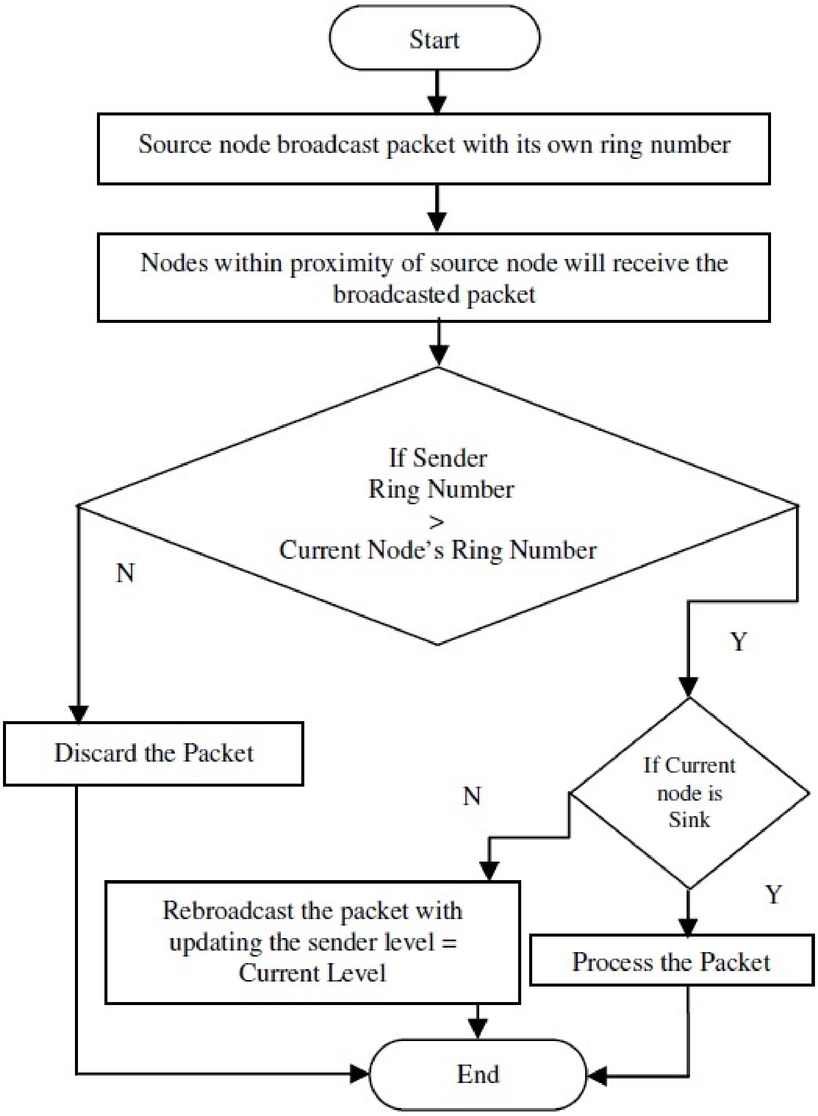


Figure 4.7 *Flow Diagram of Data Transmission Phase*

- *Not Centralized*: Apart from initial setup, no synchronization is needed for this routing protocol. Also, less overhead is required by the routing layer in order to accommodate the level/Ring number.

Disadvantages

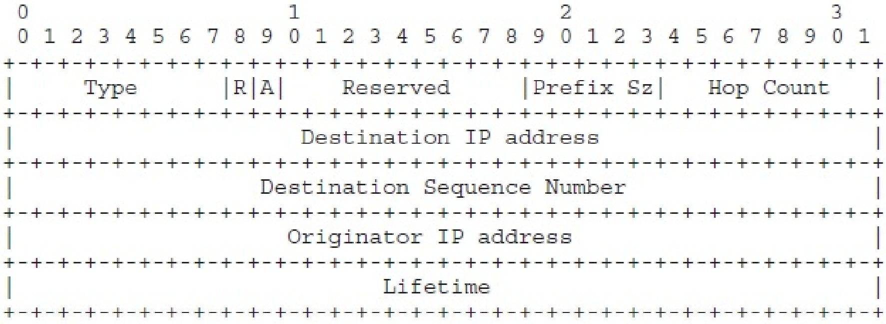
- *Unnecessary traffic*: All nodes are forwarding the same packet towards the sink, creating unnecessary traffic. This can lead to collisions and packet loss.

- *No energy information*: Nodes have no information on energy levels of the neighbors. Flooding towards the sink can lead to higher overall energy consumption.
- *No Fairness*: Nodes near to sink will have more packets to forward then the nodes away from the sink. This will lead to large number of dead nodes near the sink which can paralyze the whole network.
- *Not suitable for EH-WSN*: As mentioned above, nodes have no information about the energy levels of their neighbors. Broadcasting the packet can lead to multiple copies being forwarded by the lower level nodes (all lower level nodes will forward the packet). The lower level nodes might or might not be sleeping while the packets are being sent by the higher level nodes. Prior knowledge of the lower level neighbors will be required and unicast forwarding of the packets can give higher packet reception probability.

4.3 AODV-EHA

Energy Harvesting Aware Ad-hoc On-Demand Distance Vector Routing Protocol (AODV-EHA) [23] inherits the advantages of existing AODV (Ad-hoc On-Demand Vector) [37] protocol in dealing with WSN's ad-hoc nature and also makes use of energy harvesting property of the sensor nodes enabled with harvesters. This means AODV-EHA not only adapts to ever changing sensor network but also achieves energy efficiency in energy harvesting based network. This is achieved, by using the existing mechanism of AODV without adding complexity. Unlike AODV, AODV-EHA intends to find a path with least transmission cost (hop counts) in terms of energy. The basic procedure of both AODV and AODV-EHA is same, except in packets like Route Request (RREQs), Route Replies (RREPs) etc. The RREQ message format [37] of original AODV is depicted in Figure 4.8.

In AODV-EHA, the field named “Hop Count” is replaced with “Energy Count”. Energy Count is defined as the prediction of overall transmission cost to deliver a packet successfully from source to node handling the request. The same process will be applied to RREP message format by replacing the “Hop Count” with “Energy Count” but this time, the energy count signifies the average transmission cost to deliver a data packet successfully from source to ultimate destination. Since, AODV delivers these messages in route discovery process itself, thus no extra routing overhead is added for AODV-EHA protocol. The AODV-EHA protocol works on AODV algorithm whose primary objectives are:



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |R|A|    Reserved     |Prefix Sz|   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Destination IP address                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator IP address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                           Lifetime                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4.8 *RREQ message format in AODV Routing*

- Broadcasting discovery packets only when required.
- Differentiate between local connection management (Neighbor discovery) and general topology maintenance.
- Broadcasting information about local connectivity changes to neighbor nodes.

4.3.1 AODV-EHA operation

Initial step of AODV-EHA operation is path discovery which contains forward path discovery and reverse path discovery:

Path Discovery

This process is initiated when a source node needs to communicate with another node, for which it has no routing information in its routing table. The source node initiates the path discovery by broadcasting a RREQ packet to nearby nodes. As mentioned before, the RREQ packet will contain following fields:

$$< \text{source-addr, source-sequence-number, broadcast-id, dest-addr,} \\ \text{dest-sequence-number, energy-count} >$$

Each neighbor will either satisfy the RREQ packet and sends a route reply packet RREP or rebroadcasts it by increasing the energy-count. Even if a node is not able to satisfy the RREQ, it still keeps information on the below mentioned items in order to apply the reverse path setup, and the forward path setup that will come with the transmission of ultimate RREP:

- Destination node address
- Source node address
- Broadcast-id
- Entry expiration time
- Source sequence number

Path discovery contains two major setup phases called Reverse path setup and forward path setup.

1. **Reverse Path Setup**: Using the sequence numbers (source and destination sequence numbers) in RREQ, a path in reverse is already set up from all nodes back to source which is called reverse path. For this, a node records the neighbor's address from which it received first copy of RREQ. These entries are maintained for at least the time for RREQ to go through the network and send a reply to source. A simplified operation is shown in Figure 4.9.

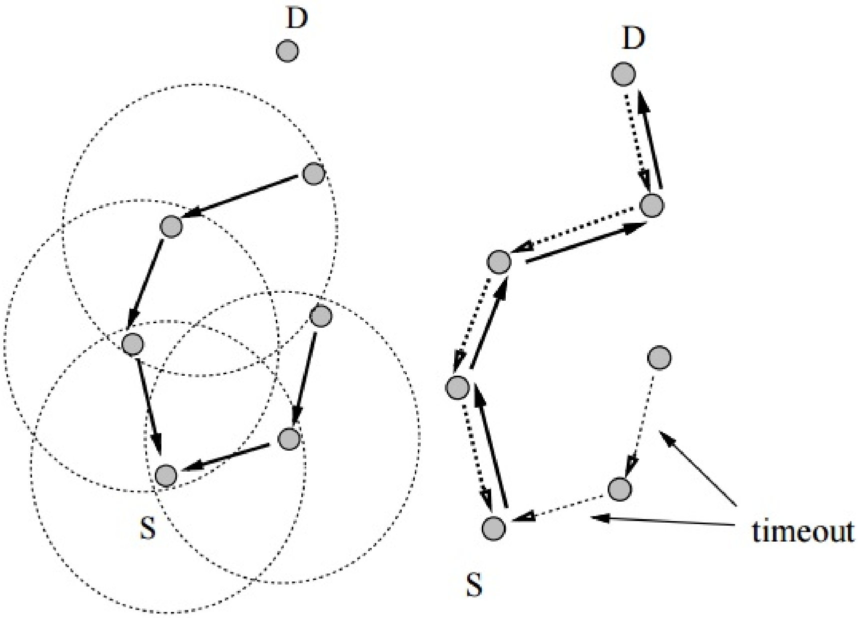


Figure 4.9 *(a) Reverse path formation (b) Forward path formation*

2. **Forward Path Setup**: RREQ will reach the destination eventually. The receiving node will first checks that if RREQ is received over bi-directional link. If the bridging or intermediate node has a route to destination already,

it will first check its own sequence number with the destination sequence in the route entry. If the route is quite old, the node should not use it and should rebroadcast the RREQ packet. The intermediate node can only reply when it has a route with sequence number greater than or equal to that of RREQ's source sequence number. If this condition satisfies, the node will send a unicast RREP packet toward source. A RREP packet will contain following information:

<source-addr, dest-addr, dest-sequence-number, energy-count, lifetime>

While RREQ transverse to a node, a reverse path is already setup. Hence, sending the RREP will not be a complex task. Source node can receive multiple RREPs for which it keeps on updating its routing information and re-broadcast the RREP only if RREP contains either a higher destination number than previous RREP or the sequence number with lesser *energyCount*. The data packet is forwarded from source node to destination using the path with less *energyCount* or high harvest rate.

3. **Route Table Management**: Other than source and destination sequence numbers, some more information is stored in route table entries. *Route request expiration timer* is one such entry and its purpose is to clean the reverse path routing entries from the nodes that does not belong to the route between source and destination. Another entry called route caching time-out is the time after which the route will be declared invalid. In every routing table entry, the active neighbor's addresses are also stored. A node is considered to be active only when it has relayed at least one packet to the destination within *active timeout period*. This helps when existing link to a destination breaks and and the neighbors are needed to be notified about alternate route.

4.3.2 Advantages and Disadvantages

Advantages

- AODV-EHA not only inherits the properties of AODV but also uses the advantages of energy harvesting feature of sensor nodes.
- Achieves both energy efficiency and can handle network topology variations. It works pretty well for networks with mobile nodes.
- It has the least transmission or routing overhead throughout the determined routes.

Disadvantages

- Unused routes expire even when topology doesn't change. Finding new paths again will be an overhead for static networks.
- Periodic updates are needed for route maintenance and discovery.
- Routes are inconsistent.
- In case of energy-harvesting feature, it makes sure to send the packet with least energy cost, which is essentially the residual energy of the node. Harvesting rate is not considered for route discovery predictions.

5. ENERGY HARVESTING BASED MULTIPATH RINGS ROUTING PROTOCOL

5.1 Introduction to EH-MPR routing

Section 4.2 defined a popular energy-efficient protocol called MPR routing which utilize the concept of flooding to transfer data packets from source to destination. Even though it is bundled with plenty of advantages for the battery powered sensor nodes, it is not efficient for EH-WSN. Therefore, a modified version of MPR routing called *Energy Harvesting based Multipath Rings* (EH-MPR) Routing is proposed which takes harvesting rate into consideration for efficient network operation. This protocol not only takes advantage of MPR routing capabilities, but also make use of the energy harvesting capability of the nodes. Simulation results has shown that energy cost of successful data packet transmission for EH-MPR routing is substantially less when compared with MPR routing protocol. EH-MPR contains the global network information as well as achieves high energy-efficiency for theoretically infinite network lifetime. All our evaluations target the applications with static nodes. New nodes can easily join the network which gives an edge over other routing protocols in case of scalability. Through EH-MPR, applications with high latency tolerance are focussed. Nodes will have enough time to harvest energy before transmitting the data packets. It can be used in applications like environmental monitoring where data is not transmitted at high rate. The rest of the chapter is organized as follows: In Section 5.2, enhancements made in MPR in order to support energy harvesting nodes are discussed and in Section 5.3, the operation of EH-MPR protocol is explained.

5.2 Enhancements over original MPR protocol

MPR routing is energy-efficient but can be modified in multiple ways for better performance in ambient energy-harvesting environment. In performance evaluations, it was found that the network can be arranged in a more efficient topology. Also, the packet forwarding scheme can be modified while considering the energy harvesting rates of network nodes. Let us now discuss the enhancements made for EH-WSN in detail:

5.2.1 Efficient ring formation

In traditional MPR routing protocol [35], sink node transmits a setup packet in the beginning of the network operation. The neighboring nodes receives this packet, set their own ring numbers (or level) and forwards the packet further. With every packet forwarding, more and more nodes will join the network at a certain ring level. This level is the hop distance of that node from the sink. EH-MPR went a step ahead for allocating an efficient ring number which will indicate nodes' distance from the Sink. A setup packet reception Threshold Th_O is assigned to network nodes which will represent the packet's received signal power threshold. Hence, when a node receives a setup packet from its neighbors, it will first check if the RSSI of the received setup packet is greater than or equal to the set threshold Th_O.

$$\text{Received RSSI of received setup packet} \geq Th_O$$

If not, it will discard the setup packet and will wait for another packet which can fulfil the mentioned criteria. The reasons which led to designing efficient ring formation scheme:

1. Receiver node receives packets from all the nodes which can transmit within the sensitivity of the radio. But packets with RSSI near to radio sensitivity might be lost in data transmission due to interference. For instance, radio CC2420 has a RX sensitivity of -95 dBm. Let us assume that a topology setup packet is received by the radio with RSSI -95dBm. In normal MPR operation, the node will accept this packet and will assign itself with the packet's ring number. But in data dissemination phase, a slightest change is RSSI will not allow the packet to reach the receiver (e.g., if RSSI of the packet changed to -96dBm due to interference) due to receiver sensitivity. This will be responsible for data loss and thus leading to low reliability. But setting a threshold to lower level than the receiver sensitivity, will have some scope for interference tolerance. In laymen terms, a boundary is set and the received

RSSIs' which are under this boundary will be considered as neighbors. It will discard the packets coming from far distant nodes. In case node doesn't receive any packets within threshold, it is being assigned the highest possible ring level. The threshold Th_O should be chosen efficiently as it can have huge effect on the data transmission rate. The method to choose Th_O through experimentation is shown in subsequent section of this thesis.

2. Through efficiency ring formation scheme, user can increase or decrease the number of rings. Network administrator can select this threshold Th_O based on the network load or node distribution over network area. Choosing high threshold will divide the network into large number of rings and vice-versa. If the network has large number of rings, overall energy consumption of the network will be low as the forwarding nodes will be closer to each other and the transmission cost will decrease. Energy harvesting nodes with lower harvesting rates can choose to have lower Th_O so that they need not to transmit over long distances. This is an explicit feature of this protocol if node is provided with power control.

5.2.2 Selective forwarding

In traditional MPR routing, data dissemination phase contains broadcasting data packet to all the nearby nodes. All the lower level nodes receive this packet and retransmits it after modifying the packet sender level. This creates multiple copies of the data packet which travels all the way to sink and is finally discarded by sink. This wastes a lot of overall energy of the nodes. Thus, a new feature of "selective forwarding" is added in EH-MPR routing to improve the energy use of the system. After topology setup phase, each node will have a table of Neighbors. This table will contain the node ID, energy level, harvesting rate and ring level. This table will be created using topology setup packet which will carry all the above mentioned information of the sender. When a node has data packet and enough energy to send it, it will go through the list of neighbors to find a potential forwarder. This potential forwarder should have minimum energy to forward all the packets and highest in the table. Harvesting rate is another metric for choosing a suitable forwarder node. The most important data field is *harvestingRate* for each node which is a function of harvesting rate and residual energy of the sensor node. It can be defined by the sum of relative energy and relative harvesting power as:

$$harvestingRate = \frac{curEnergy}{maxEnergy} + \frac{curHarvestingPower}{maxHarvestingPower} \tag{5.1}$$

where *curEnergy* is the residual energy of the node, *maxEnergy* is the maximum amount of energy storage of node, *curHarvestingPower* is the current harvesting power of harvester, *maxHarvestingPower* is the maximum power harvesting capability of the harvester.

Based on highest *harvestingRate* value, which is being sent along with the topology setup packet, a potential forwarder will be chosen. The sender node will send it as unicast rather than broadcast, addressing it to the node with high *harvestingRate* value. This will avoid the multiple copies of the same packet.

5.2.3 Neighbor's harvesting information

After a certain amount of time, the node with high *harvestingRate* might forward a lot of data packets and is on the verge of exhausted energy storage. This situation needs to be informed to all the neighbors, so that they can update their neighbor table with the new values. An extra packet called *energyUpdatePacket* will be periodically transmitted in order to update the neighbor table and its corresponding values. The period with which this packet is sent is crucial and its effects will be shown in the following sections through simulations. This packet is an overhead as it doesn't carry any data but at the same time, it serves an important purpose of updating the neighbor's table. This *energyUpdatePacket* can also be sent using dynamic time period based on the harvesting rate and residual energy of the node. Currently, this part is out of scope for this work but will certainly be an important addition for future work.

5.3 EH-MPR Operation

Unlike traditional MPR, the operation of EH-MPR consists of three phases:

5.3.1 Topology Setup Phase

This first step is somewhat similar to the traditional MPR routing phase. It is responsible for dividing network nodes into rings or levels which indicates their hop distance from the sink. But in case of EH-MPR, this phase is also responsible for nodes to update their Neighbor tables. Every node will contain a Neighbor table which will contain Neighbor's Node ID, harvest rate and ring level. An example table is shown in Table 5.1 where nodes store their neighbor's information in Neighbors' table.

Table 5.1 *Example Neighbors' Table*

Node ID	HarvestingRate	Level or Ring
3	0.758	2
8	0.652	3
11	0.123	2

In topology setup phase, a topology setup packet broadcasted from the sink. It contains all the fields similar to original MPR routing except an addition of harvestingRate field. This is considered to be a routing overhead but the energy spent in transmitting this overhead will be much lower than the overall energy saved using this protocol. The topology setup packet format in shown in Figure 5.1. Self-Node ID and Destination Node ID contain the source and destination node ID respectively. Current Sink ID will be used if the network consists of more than one Sink. Current Ring number indicates the level/Ring it belongs to in the network and Harvesting Rate is the value of *harvestingRate* from equation (5.1). This is calculated by all nodes individually.

Self-Node ID	Destination Node ID	Current Sink ID	Current Ring number	Harvesting Rate

Figure 5.1 *Topology Setup Packet Format for EH-MPR Routing*

The topology setup phase is initiated by the sink node. A topology setup packet, as shown in Figure 5.1, is transmitted with initial values where Self-node ID is set to *Sink-Network-Address*, Destination node ID is set to *Broadcast-Network-Address*, current ring number is set to Zero as sink belongs to level 0 and harvesting rate (equation 5.1) is calculated by the sink node and updated in the packet. This complete topology setup packet is broadcasted in the network by the sink node. As far as ring assignments to the nodes is concerned, the EH-MPR is exactly the same as MPR except few things. The rings are assigned on the basis of threshold Th_O as discussed before. It can be seen in the flow diagram for topology setup phase in EH-MPR routing in Figure 4.2. RSSI in the flowchart indicates the signal strength of the received setup packet.

Each node which receives this packet will update the below mentioned values in their own memory:

1. *Ring number*: The node which receives this packet will update their own ring number, i.e., *currentRingNumber* value based on the received packet's ring number.

   $$currentRingNumber = receivedRingNumber + 1 \tag{5.2}$$

   This is a general equation for updating node's own ring number as per the received packet's ring number. Hence, the nodes who receives this packet from sink will update their *currentRingNumber* as "0+1" i.e. 1. This makes sense because all the nodes who belongs to level 1 are in close proximity of the Sink and can communicate with it directly.
2. *Neighbor's table*: As shown via Table 5.1, every node keeps track of its neighbors, no matter what level they belong to. Nodes should know about all the neighbors which will help it for optimal packet transmission in data dissemination phase. As can be seen in Figure 5.2, the node first checks if the topology setup packet is above the said threshold or not. If yes, then the node will find the received packet's node ID in its neighbor's table. If not found, packet's node ID will be added into the Neighbor's table along with harvest rate and level number. By the end of this phase, each node will have its own ring number or level (its hop distance from the sink) and a neighbor table which will contain the neighbor node IDs, their harvesting rate and level they belong to. A delay is provided in the beginning of sensing operations for this phase of ring formation.

5.3.2 Data Dissemination Phase

Data dissemination phase is the stage when actual data transmission happens. Once the topology setup phase is over and nodes are assigned with ring numbers, data dissemination phase starts. In normal MPR operation, data is flooded through the network and intermediate nodes rebroadcasts it till it reaches sink. But in EH-MPR, the packet address is unicasted to one of the node in neighbor table with level is *currentLevel + 1* and *highest harvesting rate.* The step-by-step description of the protocol is shown using a flow diagram in Figure 5.3.

Based on the applications, packets are generated on-demand or periodically. Once the node has a packet to send, it will add it to the buffer. When node acquires enough energy to transmit, it will choose an intermediate destination node for the next hop. Firstly, node will go through all the neighbors in the neighbor table with level field equal to *currentLevel - 1.* If there is only one node, it will be the intermediate destination or hop destination for this data packet. But if there are multiple nodes available with level lower than 1, then:

1. *Navigate through Neighbor's table to find the nodes with level = Current Level - 1*
2. *In case of multiple results, retrieve the node with highest harvesting rate*

The node with level lower than 1 and comparatively higher harvesting rate will be considered as *potential forwarding node.* Once this decision is made, the source will send the packet to this *potential forwarder* and packet will be one hop closer to the sink. If sender belongs to level 1, the potential forwarder will be the sink which is the ultimate destination. A node will find a potential forwarder every time it has a packet to forward.

Choosing a potential forwarder and avoiding broadcasting the packet can give amazing results in terms of energy saving. It also prefers the nodes with high energy harvesting rate for forwarding tasks which puts less stress on the nodes with low harvesting rate.

5.3.3 Energy Update Phase

The topology setup phase enables the initial arrangement of network in rings or levels. Nodes also maintain their neighbor table which stores neighbor's node ID, harvesting rate and level. As the focus is on static network nodes, it is certain that node ID position and level will not change, unless a major interference blocks the transmissions. But node's harvesting rate ,due to unpredictable incoming energy, and residual energy ,due to charging and discharging of supercapacitor, continuously varies over time. The residual energy can be tracked but harvesting rate is immensely unpredictable and might change very frequently. Hence, there is a need to update the neighbor table with latest harvesting rate values. It is done by broadcasting an energy-update packet which is necessarily a topology setup packet with latest values of harvesting rate. The new nodes can also join the network through this phase and existing nodes can send their updated energy harvesting values to nearby nodes.

For the simplicity of EH-MPR routing algorithm, the energy update packet is transmitted periodically. The administrator can control this period for better performance. For future work, more complex algorithms can be created which can intelligently estimate this period based on energy harvesting predictions and current energy usage.

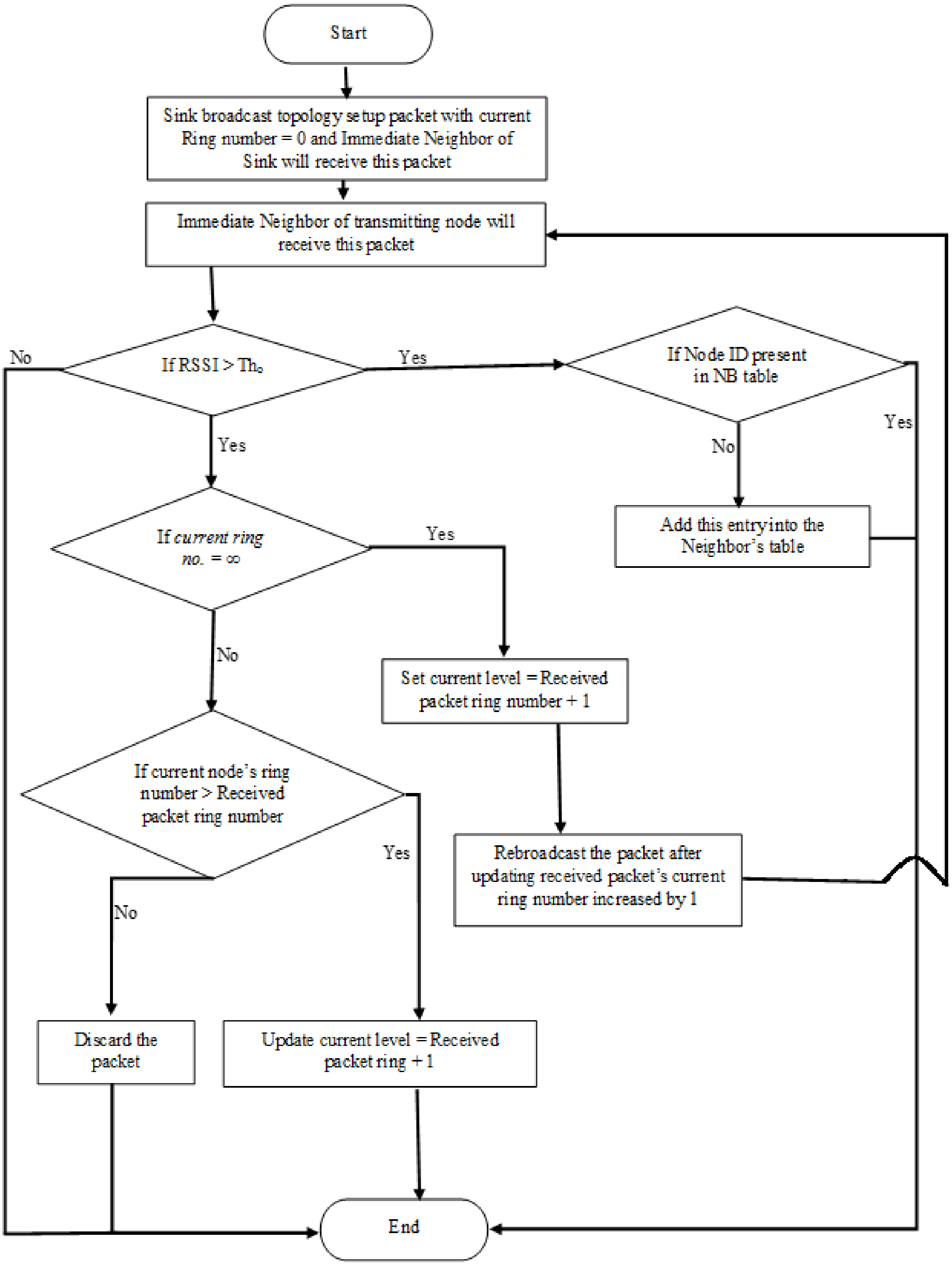


***Figure* 5.2** *Flow diagram of topology setup phase in EH-MPR routing*

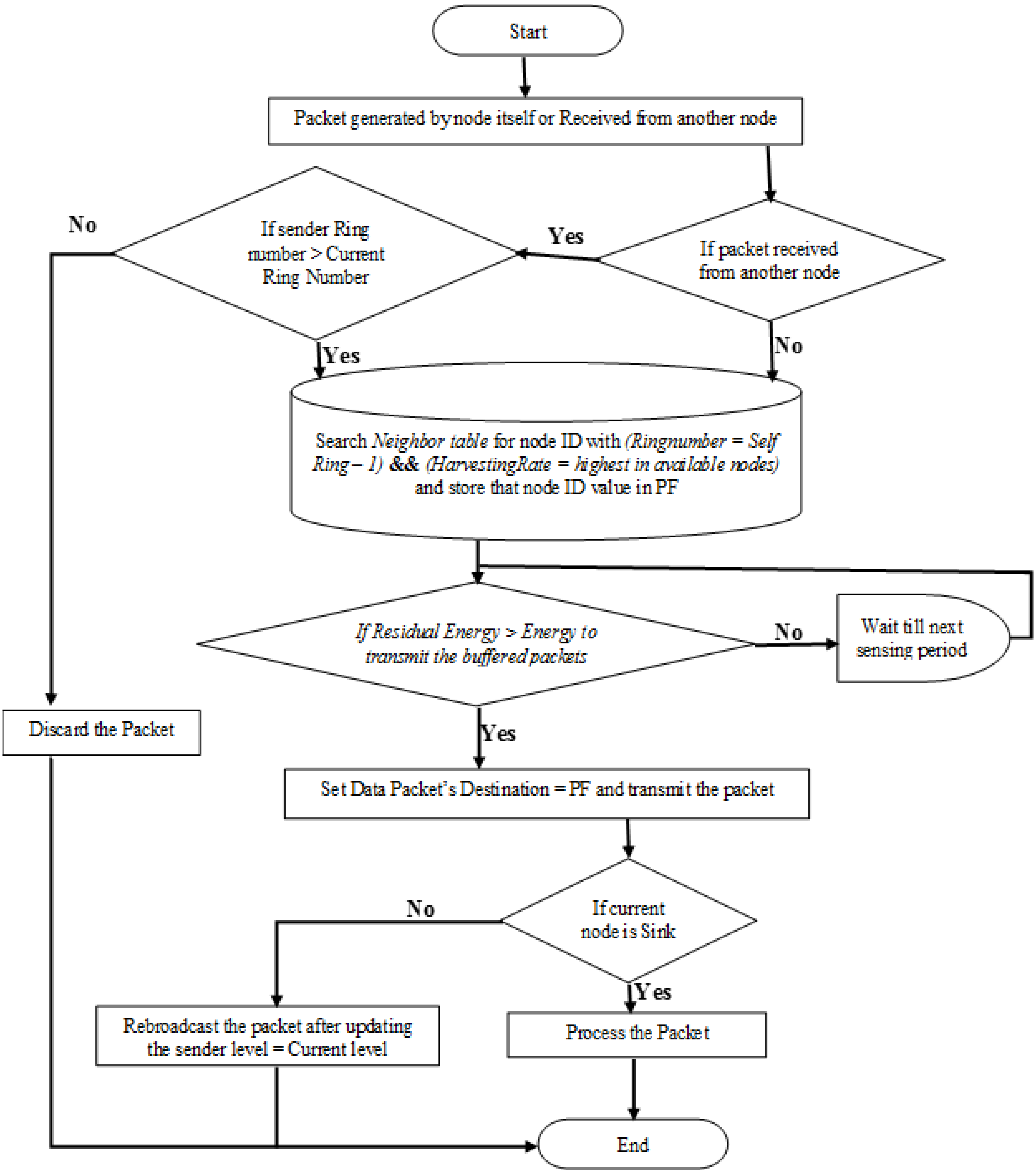


Figure 5.3 *Flow diagram for Data Dissemination Phase in EH-MPR*

6. PERFORMANCE EVALUATION OF EH-MPR THROUGH SIMULATIONS

6.1 Simulation environment

There exists a plethora of multiple simulation platforms and frameworks that provide comfortable simulation environment for different WSN applications. In context of this work, our interest was towards the modularity, realistic radio and wireless channel models and comfortable programming. After some research, OMNET++ [46] based Castalia [9] is chosen to be our simulation environment as it provides a simple platform to perform "first order validation of an algorithm before moving to an implementation on a particular platform". OMNET++ is a discrete event simulation environment that is specifically suited for this specialized research field. For examples, it supports the mobility framework to simulate the realistic mobile networks, or the INET framework that models several internet protocols. OMNET++ is coded in C++ and provides the user with the graphical environment that facilitates the development and debugging. In addition, there is a wide community of developers providing support and updates for new framework. The comfortable coding environment (C++), modularity and easy training options led us to choose OMNET++ and thus Castalia for our simulations. In the following, Castalia is discussed in detail along with its architecture and changes made in the energy module in order to support energy harvesting.

6.1.1 Castalia

Castalia is an OMNET++ based simulator which is used to simulate the WSNs, Body Area Networks (BAN) and any general networks of low power embedded devices. Castalia uses OMNET++ features to define the complete architecture of a sensor node. Castalia is easier to use if the user is familiar with the OMNET++

basics, but it is not essentially needed. It can be used by the researchers and developers who wishes to test their algorithms and protocols in realistic wireless channel and radio models, with a realistic node behavior especially relating to radio access. Castalia can also be used for defining and evaluating different platform characteristics for multiple applications, because it is highly parametric and can simulate a wide range of platforms. Castalia provides with multiple features for simulating wireless networks:

1. *Advanced Channel model*: Castalia provides an advanced channel model which is based on empirically measured data.
2. *Advanced Radio Model*: Properties of real life radios are used for low power communication. User can change the radio model as required.
3. *Sensing Modelling*: Highly customizable and flexible model for defining physical processes like sensing. The factors which can be customized are sensing device noise, bias and power consumption by sensor.
4. *Clock drift modelling of the node.*
5. *Multiple MAC and routing protocols are available. New protocols can be added.*

The basic structure of Castalia is shown in Figure 6.1. Nodes in Castalia connect to each other through the wireless channel module and arrows signify the message transfer from one module to another. When node transmits packet, it first goes to wireless channel which is responsible for deciding the next node and the other properties like interference, RSSI of the packet received etc.

Figure 6.2 shows the composite structure of a wireless sensor node. The solid arrows indicate message passing and the dashed arrows signify a function calling. For example, most of the modules call a function of resource manager to signal the energy consumption. The application module, routing and MAC protocols are the ones which users normally modifies as per the need. Mobility manager is also a good candidate for modification for network with mobile nodes. As mentioned before, Castalia supports building customized protocols or application by defining appropriate abstract classes. All the available modules in Castalia are highly tunable by many parameters. The structure shown in Figure 6.2 is implemented in Castalia using OMNET++ NED (NEtwork Description) language code. Using the NED

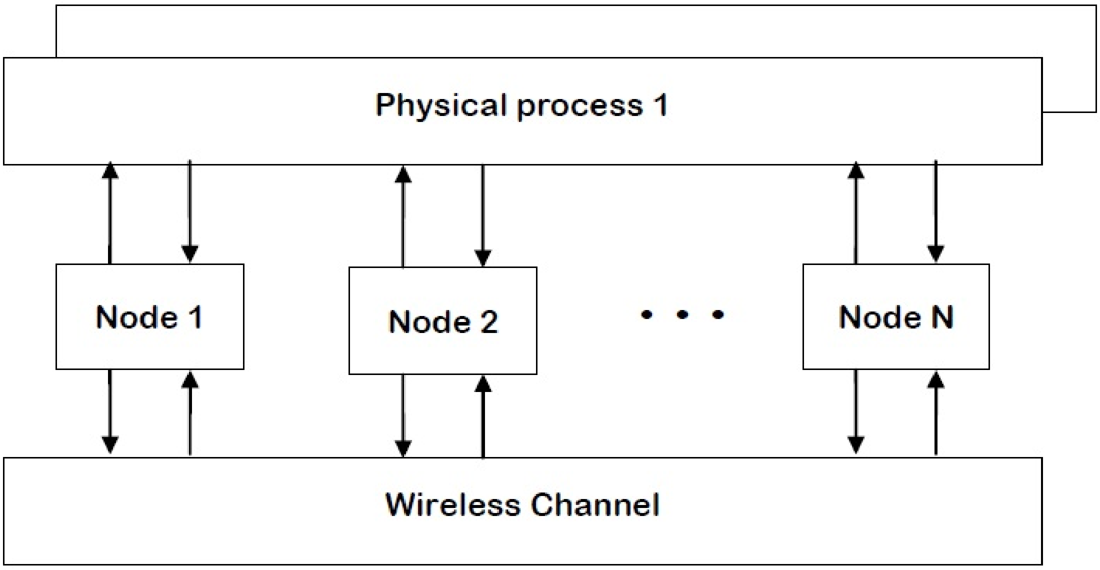


Figure 6.1 *Castalia Structure - Modules and their connections[9]*

language, modules can be defined, i.e., defining a module name, parameters and module interfaces like gates in and gates out and submodules if required. Castalia's structure can also be seen through the hierarchy of directories in the source code. The NED language code can be easily identified by checking the .ned file extension. Every module in Castalia source code contains a .ned file that define the module properties. In case of composite modules, subdirectories are present of define submodules. Castalia structure is defined by this hierarchy of .ned files. They are loaded dynamically by the system and hence, any change in these files will not require any recompilation.

6.1.2 GreenCastalia-Extention for EH

The emerging energy harvesting methods for replacing power sources in embedded devices comes with the need for dedicated simulators that can support the developers in designing and evaluating the energy harvesting aware protocols for WSN. GreenCastalia [7] is an open source energy harvesting based simulation framework developed for Castalia simulator. It supports multi-source , multi-storage and multi-harvester configuration for a node. In order to make Castalia Energy-Harvesting friendly, it was necessary to modify the *ResourceManager* module in Figure 6.2.

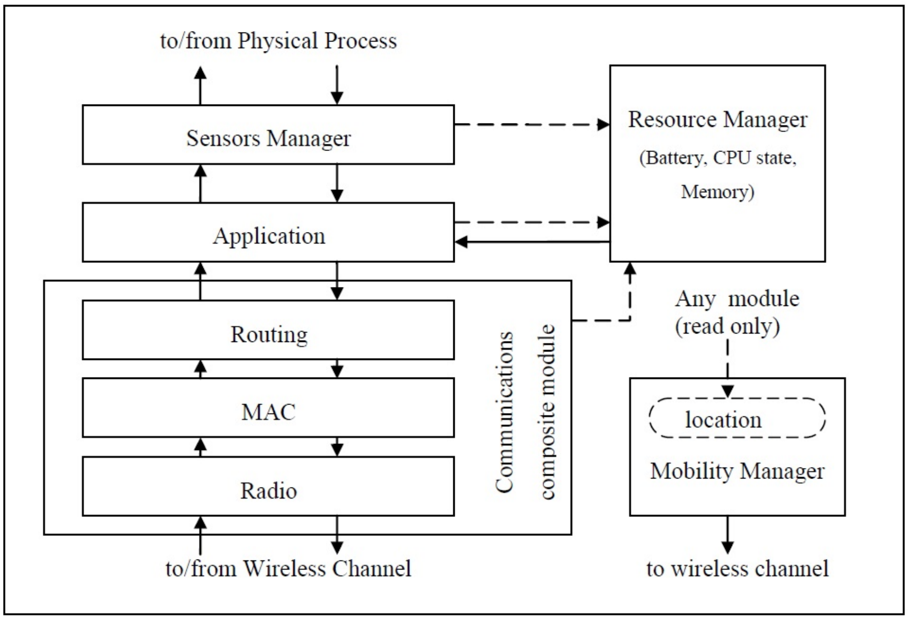


Figure 6.2 *Internal structure of Sensor node in Castalia[9]*

Hence, developers extended Castalia's energy module by introducing a sub-module called *EnergySubsystem*, which is shown in Figure 6.3. As far as energy management is concerned, this module partially replaces the *ResourceManager* module. To support all Castalia related energy functions, *ResourceManager* module is kept in the heirarchy along with the new *EnergySubsystem* module.

Ambient energy sources are also modelled through *EnergySource* module which can have multiple instances in case of multi-source harvesting systems. GreenCastalia allows users to run the simulations by feeding timestamped energy source values collected through real-life measurements [11]. It is done by generic *TraceEnergySource* module using energy availability traces obtained from data repositories. Here, every harvester present in a node is connected to just one energy source (logically true), while multiple harvesters can be connected to the same source i.e. harvest energy from the same source. User is free to declare more than one source for the network and nodes can contain multiple harvester of same or different kind.

Figure 6.3 displays the architecture of *EnergySubsystem* module. Let us briefly describe the properties of these submodules and the values it can support.

- **EnergyHarvester**: This module represents a physical harvesting device connected to a sensor node. The implementation in GreenCastalia contains an

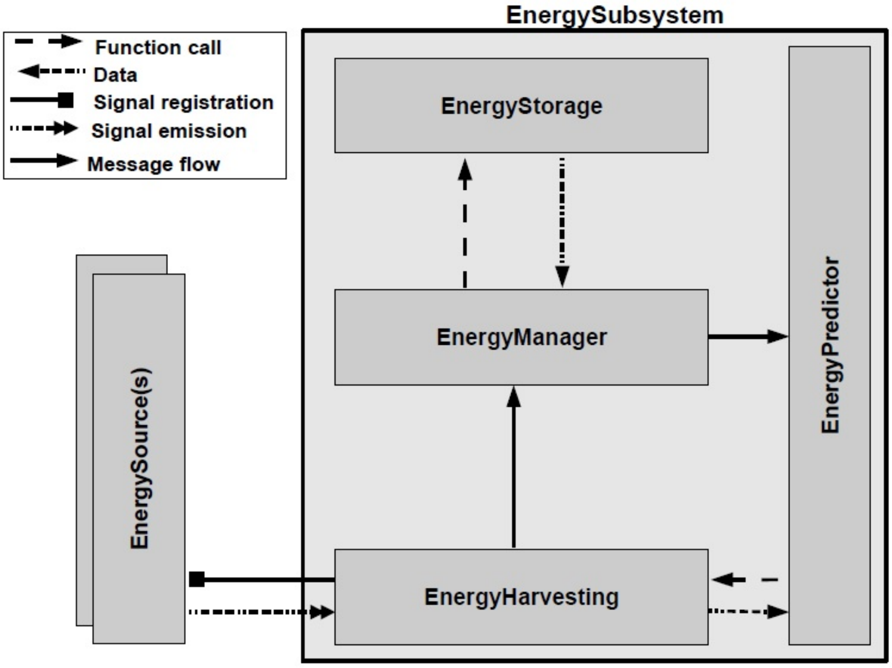


Figure 6.3 *Architecture of EnergySubsystem module[7]*

EnergyHarvester module which harvests energy from the environment (the energy source) with a particular efficiency. It is possible to feed harvesters with timestamped data file that will specify how the harvesting capabilities or device efficiency will vary over time.

- **EnergyStorage**: EnergyStorage module represents the storage device in a node. The default interface can include parameters like charging efficiency, discharging efficiency, rated capacity, max and cut-off voltage. It implements two battery models (Ideal and Empirical) and a supercapacitor model as follows:

$$E(t) = \frac{1}{2} \times C \times V(t)^2 \tag{6.1}$$

where $E(t)$ is energy stored at time t by capacitor, C is the capacity of capacitor in Farads and $V(t)$ is voltage across this capacitor. More accurate models like in [27] can be implemented, simply by extending *SuperCapacitor* module.

- **EnergyManager**: *EnergyManager* is the core of *EnergySubsystem*, which have the complete view and control of power harvesting and consumption over time. It is responsible for controlling the logic for energy storage functions like, charging and its usage. It simulates transfer of energy from harvesters and storage devices to the load, and from energy harvesters to storage device.

- **EnergyPredictor**: EnergyPredictor module provides the user with basic prediction tools which can help in designing and simulating the harvesting aware protocols. By forecasting the energy intake by a node, proactive power management strategies can be implemented in order to optimize the available energy usage. The current implementation includes the famous EWMA prediction algorithm [17] and WCMA [38].

6.2 Wireless Channel and Radio Model

Castalia contains the most realistic wireless channel properties. The average path loss between the nodes is calculated using the log-normal shadowing model. Log normal path loss is proportional to distance between the transmitter and receiver as well as few more parameters:

$$PL(d) = PL(d_0) + 10 \times \eta \times \log_{10}(\frac{d}{d_0}) + X_\sigma \tag{6.2}$$

where $PL(d)$ is pathloss at distance d, $PL(d_0)$ is the pathloss at distance indicating the rate at which pathloss increases with distance d_0 (known), η is the path loss exponent, and X_σ is gaussian zero-mean random variable with standard deviation σdB. The values considered in upcoming simulations are shown in Table 6.1. Radio parameters used in the simulations are outlined in Table 6.2. This environment is simulated to showcase the effects of varying transmitter power. As can be seen in Figure 6.4, result shows that using low power can give us satisfactory results for low data rate networks.

Table 6.1 *Wireless Channel parameters*

Parameter Name	Value
Pathloss Exponent η	1.6 (Indoor)
Pathloss PL(d_0)	55 dBm
Reference Distance d_0	1 meter
Standard Deviation σ	4.0 dB

Table 6.2 *Radio parameters*

Parameter Name	Value
Receiver Sensitivity	-95 dBm
Modulation Type	PSK
Bits per symbol	2
Noise Floor	-114 dBm (BW = 1MHz)

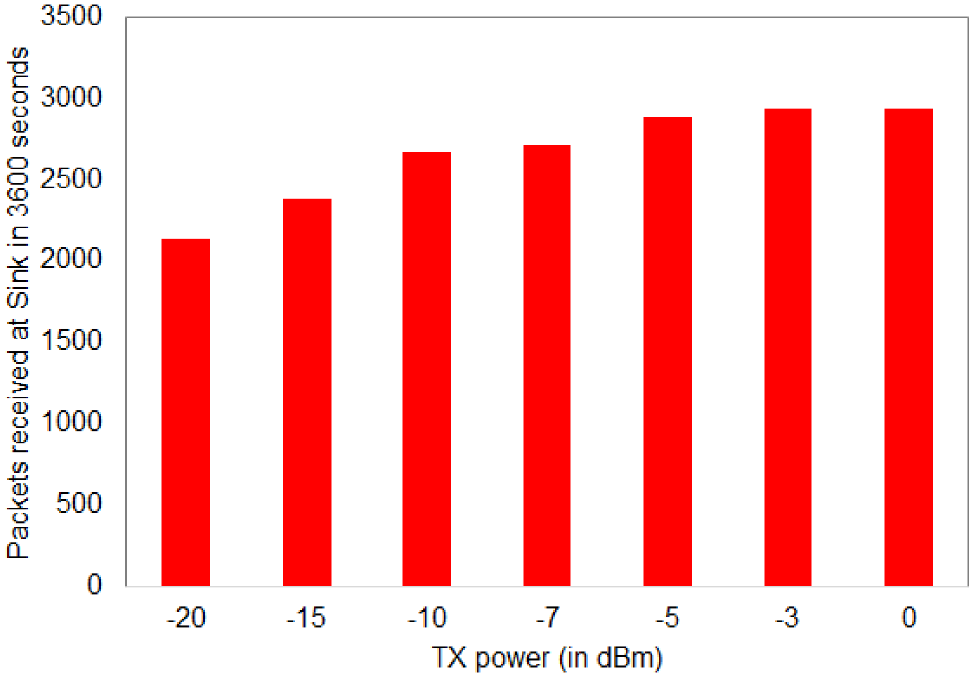


Figure 6.4 *TX power versus Packets received at Sink*

6.3 Carrier Frequency and Data Rate Analysis

EH-MPR protocol is simulated for varied values of data rate and node densities to evaluate the packet reception at sink. In first such simulation shown in Figure 6.5, packet loss rate is evaluated for varying number of nodes in the network of size $50 \times 50m^2$. The frequencies used in simulations are 433 MHz, 868 MHz and 2400 MHz which are the most popular carrier frequencies globally. In low network densities, data reliability of lower frequencies is high when compared to higher frequencies. Transmission coverage for low power nodes is very small and cannot transmit directly to the sink. Therefore, for the low density networks, most of the data packets are lost due to low RSSI at the receiver. But as the number of network nodes is increased, multi-hop transmissions decreases the packet loss rate. As apparent from the simulation result, on increasing the number of nodes, loss rate decreases as moderate node density enables multi-hop data exchange. After a certain network size, packet loss rate increases due to increasing traffic and packet collisions. In our case, when the node density becomes higher than 80 nodes in $50 \times 50m^2$ area, the data traffic and loss rate increases non-uniformly.

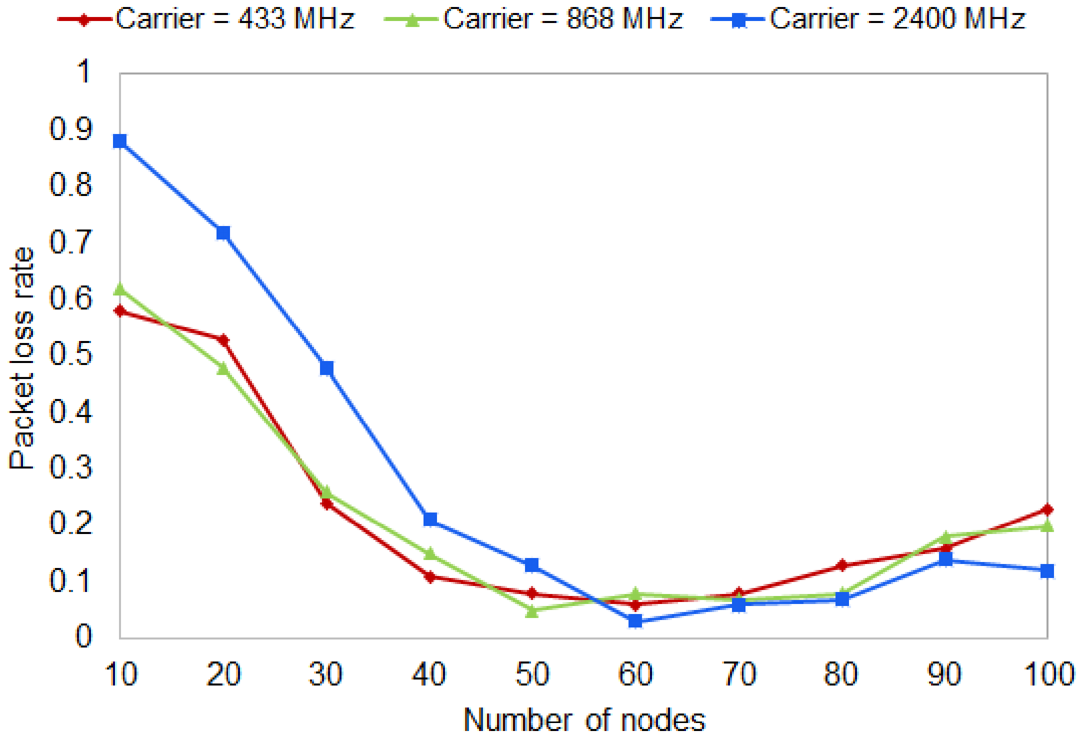


Figure 6.5 *Node density versus Packet loss rate for varied Carrier (MHz)*

The packet loss rate is defined as the ratio of packets lost (which doesn't reach sink) to total packets transmitted by all network nodes. Most of the radios available in the market has a data rate of 250 kbps. But as this research focusses on low data rate communications, a network with low data rates of 1 kbps to 20 kbps are simulated for varied packet sizes of 128 bytes, 256 bytes and 512 bytes. It is evident from Figure 6.6 that for very small values of data rate, the packet reception rate is low but as data rate is increased, packet reception also increases. At a certain point, the packet reception rate becomes close to maximum, irrespective of the packet size.

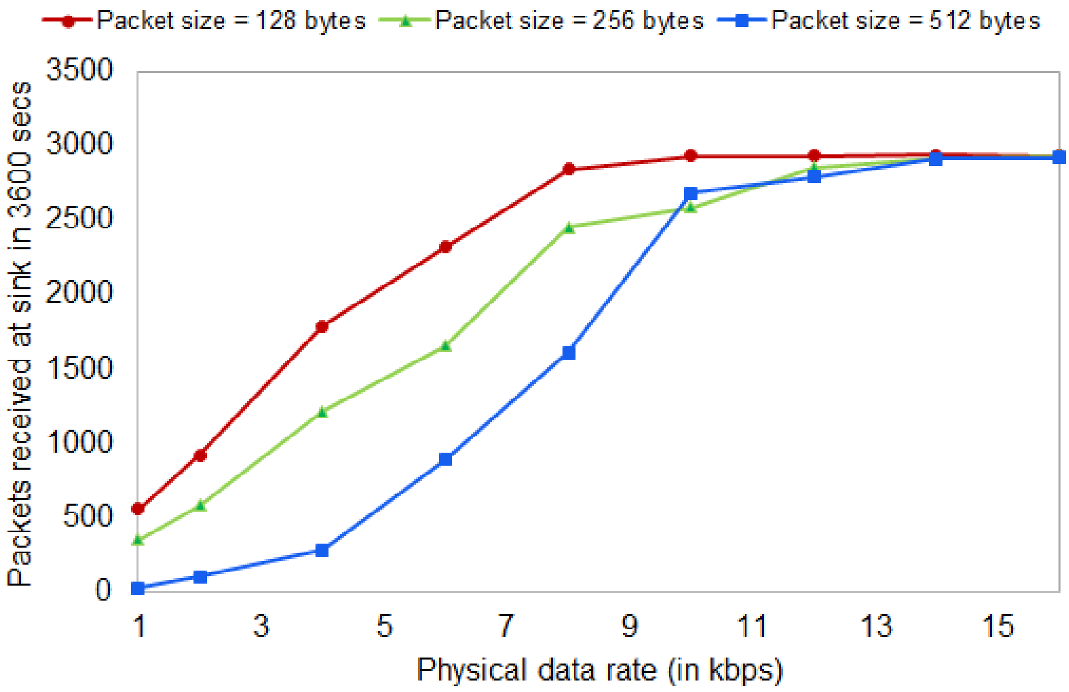


***Figure* 6.6** *Physical Data Rate versus Packets Received at Sink*

6.4 Simulation Setup

Table 6.3 shows the parameters used for the simulations. We have used a constant harvesting rate of 5 μW for all the nodes. It should be noted that in real life applications, harvesting rates are different for different nodes based on their locations and time. T-MAC with adaptive duty cycling is chosen as it performs well in varying traffic conditions. The placement of nodes in the sensor field is shown in Figure 6.7. The nodes are distributed uniformly with the sink node placed in the center for data collection.

6.5 Choosing threshold Th_o for efficient ring formation

As mentioned in Chapter4, the original MPR routing is enhanced with efficient ring formation. There is a need to choose the best value of threshold Th_O for most optimized results. Hence, the network is simulated with multiple values of threshold Th_O to find the best possible value. A decision on choosing Th_O is made on the basis of number of successful transmission i.e. number of packets reaching sink

Table 6.3 *Simulation Setup Values*

Parameter Name	Value
Simulation Time	3600 Seconds
Area	50m x 50m
Number of Nodes	50
Sensor Placement	Uniform Distribution
Sink Node	Node 0
Sink Location	Center
Application Packet Rate	1 packet per 60 seconds
Packet Size	128 bytes
TX Power (in dBm)	-10
TX power	0.1 mW
RX power	0.1 mW
Data Rate	10 kbps
Bandwidth	1MHz
MAC	Timeout-MAC
Harvesting Rate	5 μW
Energy Update Timeout	300 seconds

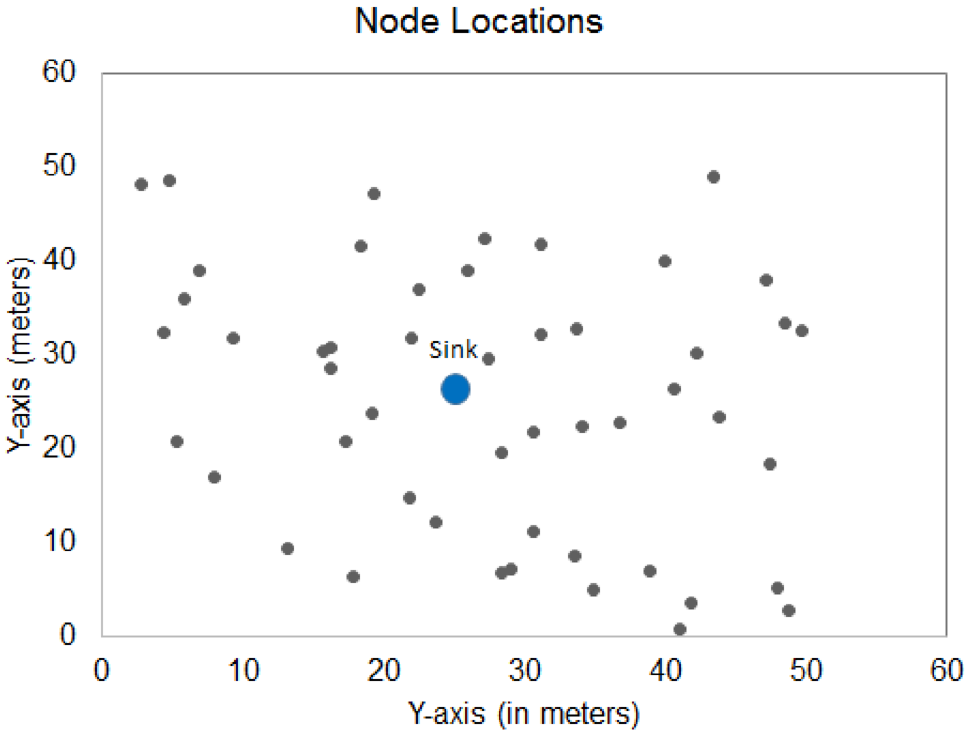


Figure 6.7 *Node distribution in Sensor field*

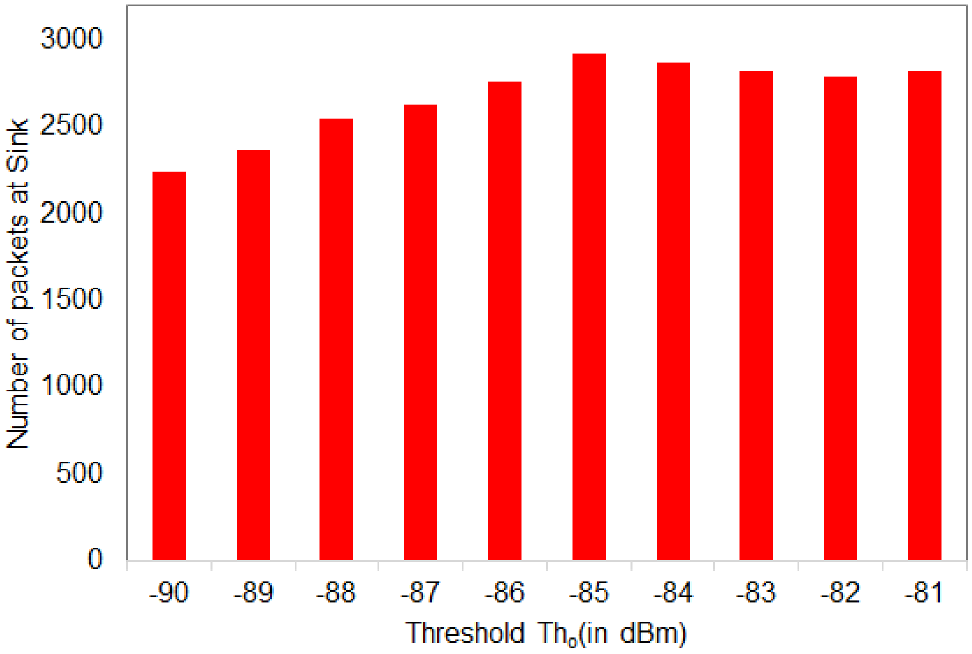


Figure 6.8 *Number of Data Packets at Sink versus Threshold* Th_o

in 3600 seconds. The protocol is tested with 10 different values of threshold Th_O from -81dBm to -90dBm. The simulation result in Figure 6.8 shows that maximum successful packet transmission happened for Threshold value -85dBm. Therefore, the threshold value for all upcoming network simulations is set to $Th_O = -85dBm$.

6.6 Comparing T-MAC and S-MAC

EH-WSN networks are not reactive and can function only when the nodes have harvested enough energy from the environment. When the stored energy exhausts, node goes into sleep to harvest energy. But applications, as in our case, might generate packets periodically which will be stored in a buffer till next transmission. Similarly, the packets received from upper level nodes are also stored in the buffer which needs to be forwarded to the lower level nodes. This will accumulate multiple data packets in node's buffer and hence, radio should be ON for transmitting all these packets. This situation creates a need when active cycle of radio should be based on the packets in the buffer. Duty cycle should be big enough to accommodate data transmission and reception of all the packets. Using MAC protocols with static or fixed duty cycles comes with a requirement to change it manually based on

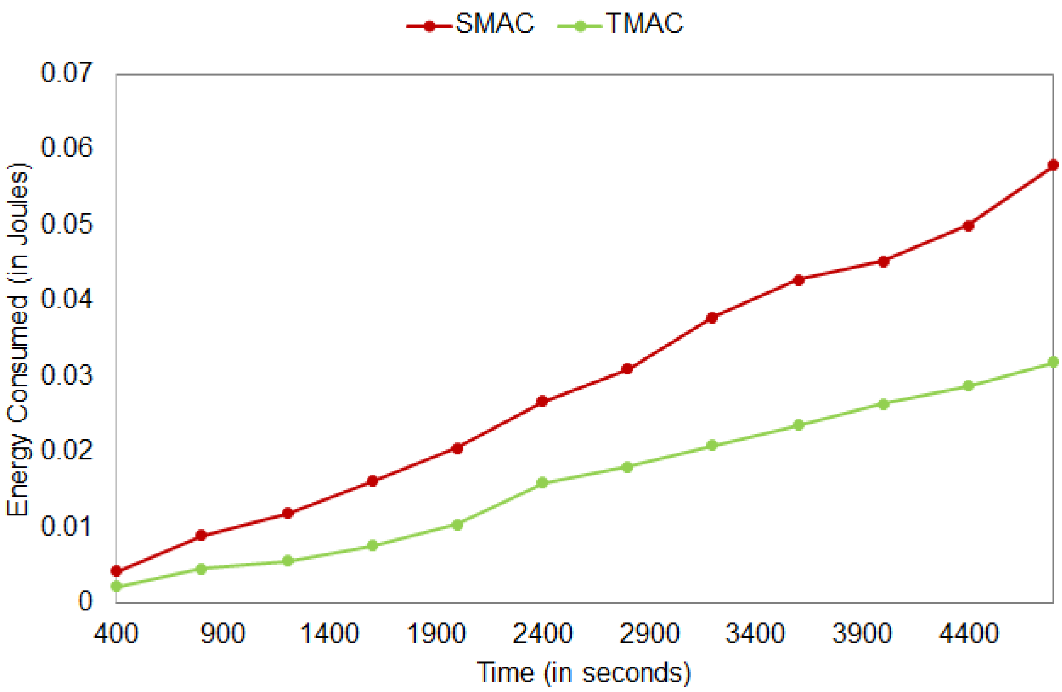


Figure 6.9 *Energy consumed (J) versus Simulation time (seconds)*

traffic and, user should know about the traffic in prior. Sensor-MAC (S-MAC) and Timeout-MAC (T-MAC), representing static duty cycle and adaptive duty cycle respectively, are compared with the help of simulations. Both of these protocols are based on Synchronizations, Acknowledgements, RTS/CTS and are described thoroughly in Chapter 4. T-MAC has the capability to adapt and extent its duty cycle based on traffic. Hence, a minimum active time is set for a node, which can increase dynamically based on the traffic. This part of simulations contains EH-MPR routing as routing protocol. The failed packets are a combination of all possible packets including *SYNC, RTS, CTS and DATA*.

Results in Figures 6.9, 6.10, 6.11 shows that T-MAC outperforms S-MAC in multiple factors. Figure 6.9 depicts the overall energy consumption by sensor nodes over time. In comparison to S-MAC, T-MAC proved to be more energy efficient. Due to fixed duty cycle of S-MAC, lots of packet will not be transmitted if receiver fall asleep. Retransmission of such packets will cost huge amount of energy to transmitter, leading to high energy consumption and failed packets in S-MAC. As far as received data packets are concerned, T-MAC has proved to be a better candidate again, as can be seen in Figure 6.10. These data packets are received by sink which

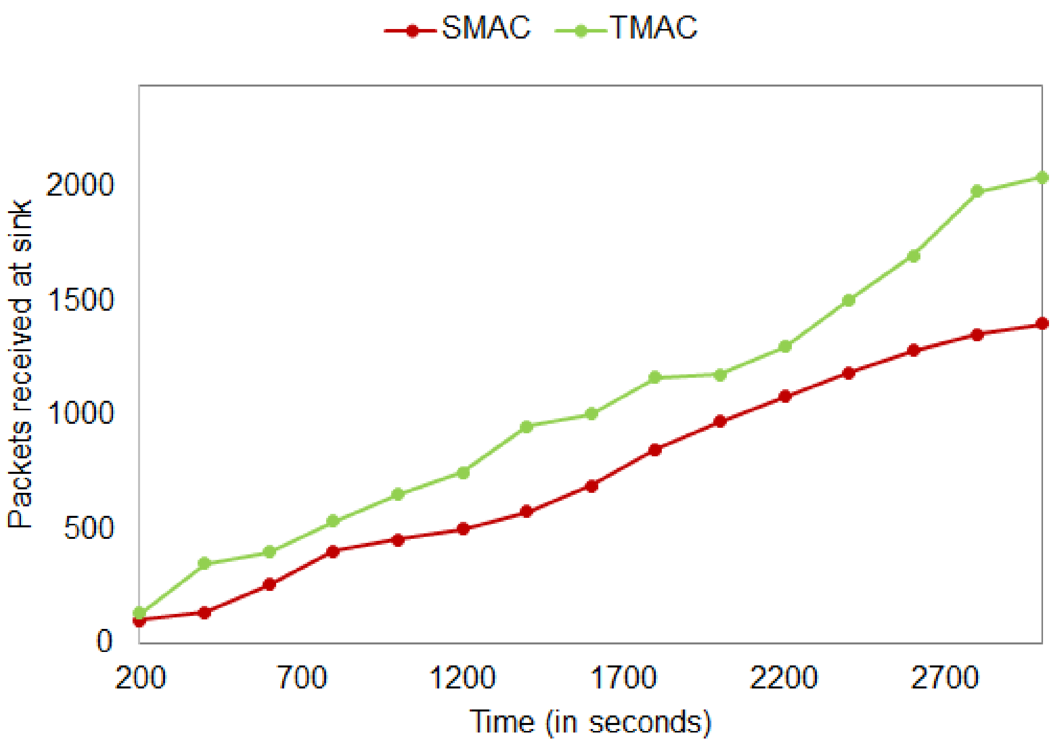


Figure 6.10 *Data packets received at Sink versus Simulation time (seconds)*

Table 6.4 *MAC parameters*

Parameter Name	**Value**
Frame Time	610 ms
Active Time(TMAC)	15 ms
Active Time(SMAC)	61 ms
Activation Timeout TA(TMAC)	15 ms
Contention Period	10 ms
Resync Time	6 seconds
Collision Resolution	Next frame retry(aggressive collision avoidance)
Maximum Retries	2

belongs to center of the network field. Next point of comparison is number of failed packets in Figure 6.11. There are four main reasons when a radio doesn't receive the packet:

- Failed even without interference
- Failed due to interference

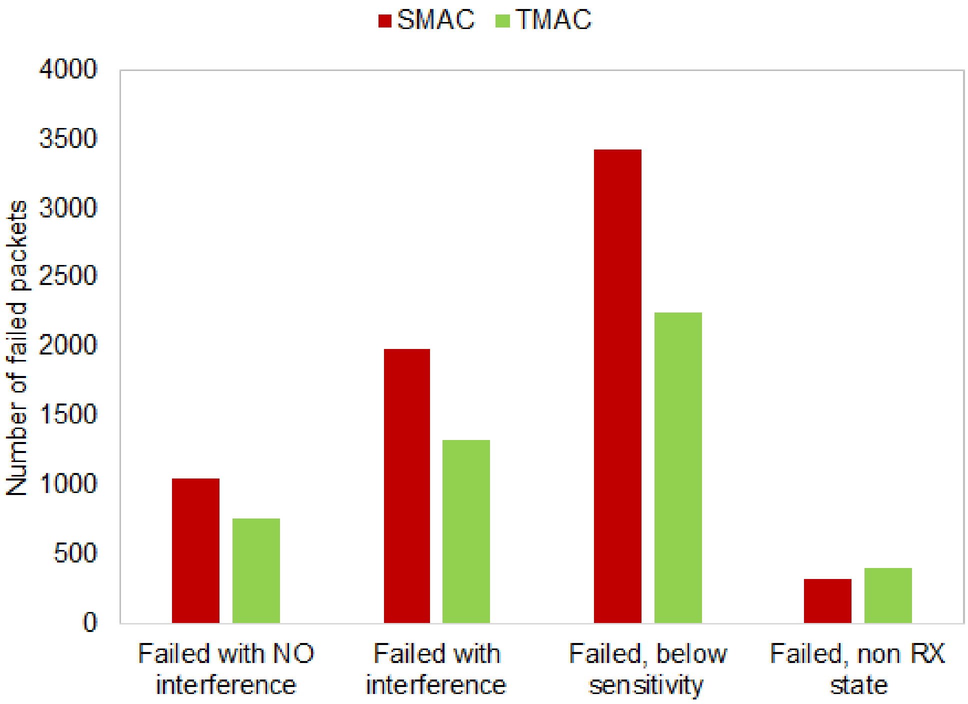


***Figure* 6.11** *Failed packets for S-MAC and T-MAC*

- Failed, below sensitivity of the radio
- Failed, non RX state because the radio was sleeping

Due to very small initial duty cycle in TMAC, early sleeping problem leads to shutdown of destination's radio even when the source is about to send an RTS packet. A possible solution for this behaviour is by informing the destination about the available packet well in advance [18]. The difference of failed packets due to non RX state is very small when compared to rest of the failed packets. Overall, T-MAC is proved to be a better MAC candidate for energy harvesting based sensor networks.

6.7 MPR Routing versus Proposed EH-MPR Routing

It is assumed that all nodes are harvesting a constant amount of energy i.e. $5\mu W$ and network consists of only static nodes loaded with a supercapacitor of maximum volts of 2.7V, capacitance of 1F and charging and discharging efficiency of 0.8 and 0.9 respectively.

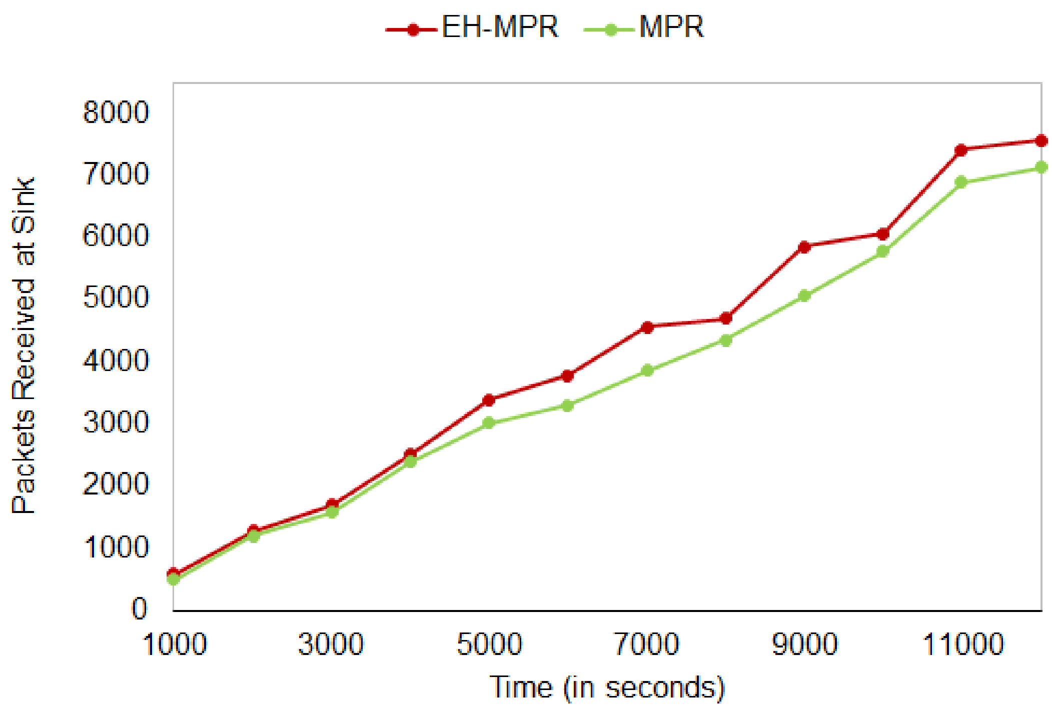


Figure 6.12 *Data Received at Sink versus Simulation Time*

Figure 6.12 shows the number of data packets transferred from network's sensor nodes to node 0, i.e., total number of data packets collected by sink. Number of packets reached sink by using EH-MPR is higher than that of MPR, although, the difference in the received packets for both the protocols is very small. The same scenario is simulated for longer period where, for all cases, EH-MPR protocol performs better than MPR protocol. Another point of comparison is the overall consumed energy for EH-MPR and MPR which is shown in Figure 6.13. For this, energy consumed by all network nodes are collected and compared with each other. In Figure 6.13, it is evident that energy distribution across network nodes is non-uniform in MPR routing. This is due to the topology of static nodes which forces the same traffic distribution, overloading just some specific nodes in the network. While for the same simulation parameters, the traffic load is almost uniform in EH-MPR routing. Also, the overall energy consumed using EH-MPR is nearly half to energy consumed in MPR and therefore, EH-MPR is clearly more energy-efficient.

For proper EH-WSN operations, the ENO state should be maintained. For obvious reasons, data transmission rate of a node is directly related to the energy consumed

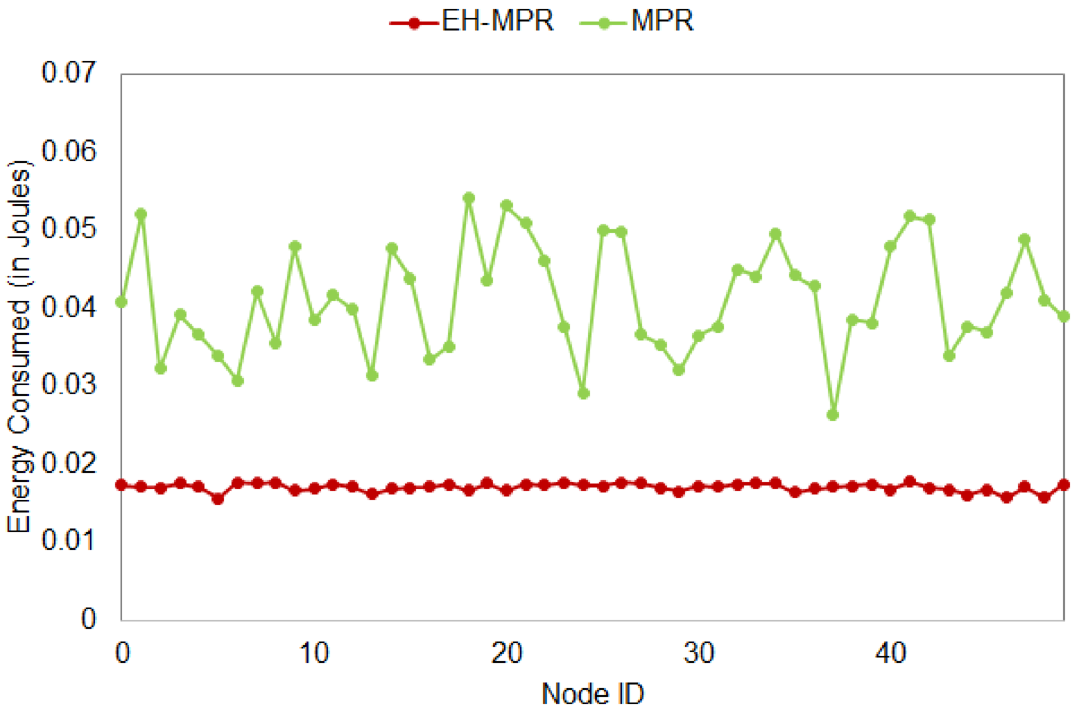


Figure 6.13 *Energy consumed (Joules) for different network nodes*

by the node. When the data transmission rate increases, more packets are generated and transmitted and the rate of relaying those packets increases. For simulations, data transmission rate of 1 packet per 60 seconds is used. This value should be able to change dynamically based on the harvested energy, though this part is out of this thesis's scope. Another metric called *HarvestedToEnergyConsumed* is evaluated which indicates the efficient use of harvested energy as well as the optimized performance with the available energy. *HarvestedToEnergyConsumed* is calculated as shown in Equation 6.3.

$$HarvestedToConsumedRatio = \frac{Total\ energy\ harvested\ (inJoules)}{Total\ consumed\ energy\ (inJoules)} \tag{6.3}$$

The ratio is different for different nodes and it can be seen in Figure 6.14. This ratio is around or equal to 1 for EH-MPR which assures a continuous network operation while the ratio is small for traditional MPR (approximately 0.5). Any ratio below 1 will lead to the energy breakdown for that node at some later time and therefore, MPR is not suitable for given network conditions. The last performance metric is the overall failed packets in a network which is shown in Figure 6.15. There are

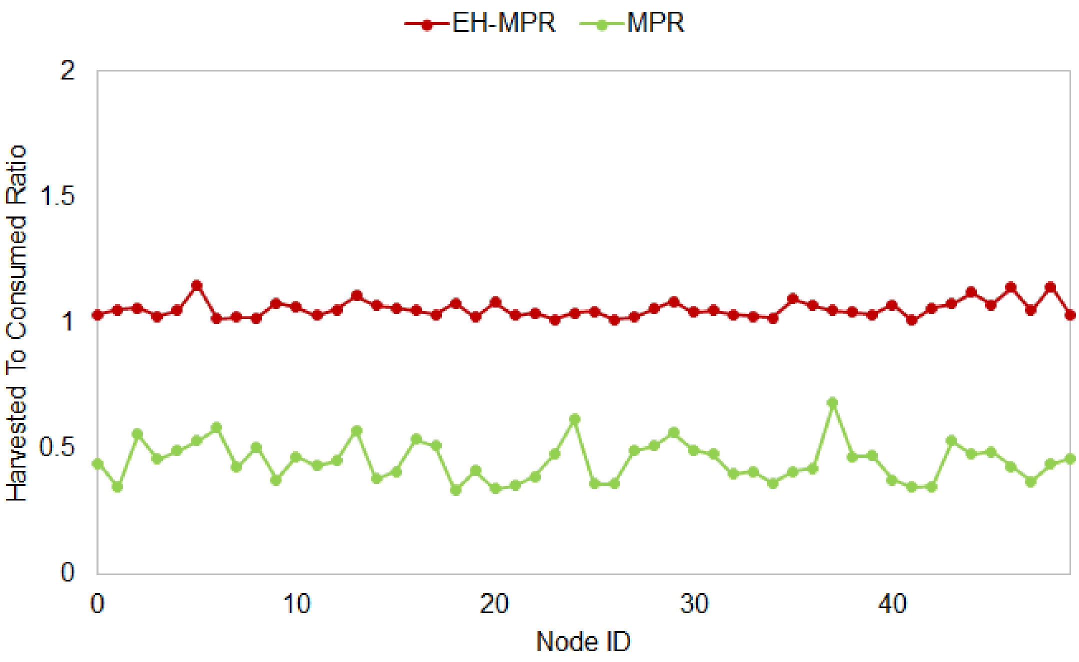


Figure 6.14 *Harvested-to-Consumed Ratio for different network nodes*

multiple reasons for packet failures in a network which are mentioned in section6.6. MAC and Routing protocols uses their own packets first to assure a successful packet transmission. MAC protocols includes SYNC, RTS, CTS and ACK which are part of T-MAC protocol. When a data packet transmission is failed, i.e., no ACK is received by the sender, it is being re-transmitted by the sender. Hence, all MAC and Routing related packets are being retransmitted. This leads to large number of failed packets for MPR. This is the main reason for higher energy consumption in MPR protocol when compared to EH-MPR. Overall, EH-MPR routing protocol overcomes the shortcomings of traditional MPR protocol for optimized results.

Packet injection rate is defined as number of packets transmitted in one second. In EH-WSN, nodes needs time to replenish energy before sensing and transmitting a physical quantity. Hence, all packet rates used in these simulations are less than 1. Figure 6.16 depicts the harvested to consumed ratio for EH-MPR on varying packet rates. For our simulations, packet rates lesser than 1/60 are suitable for maintaining the ENO state (a functional network without outage) while the packet rates higher than 1/60 are not able to maintain ENO state and are below *harvested to consumed ratio* of 1.

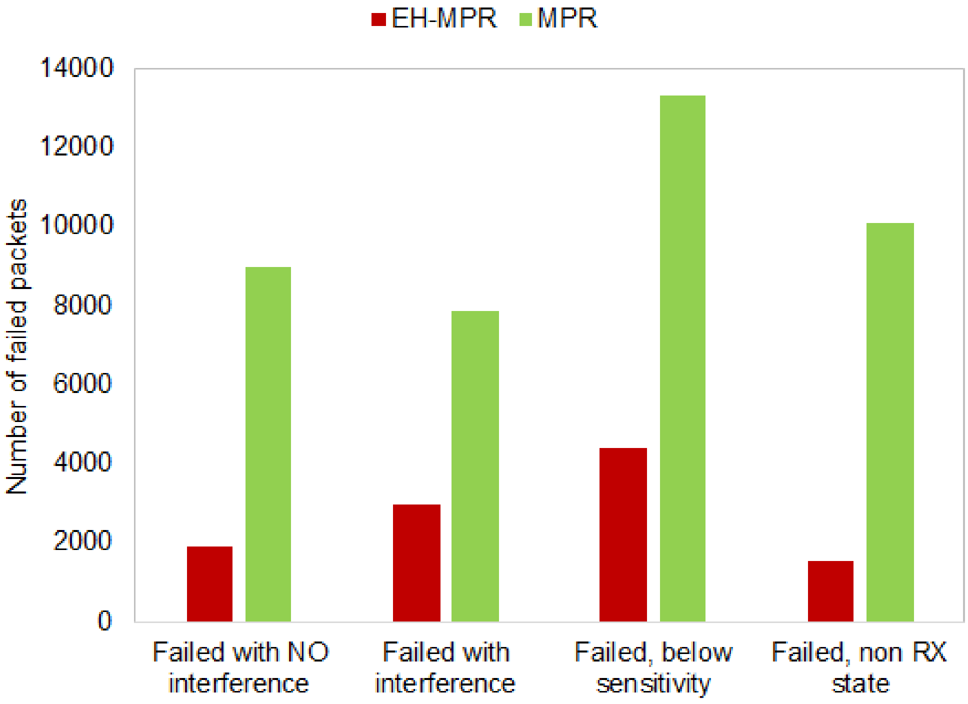


Figure 6.15 *Failed packets for EH-MPR and MPR routings*

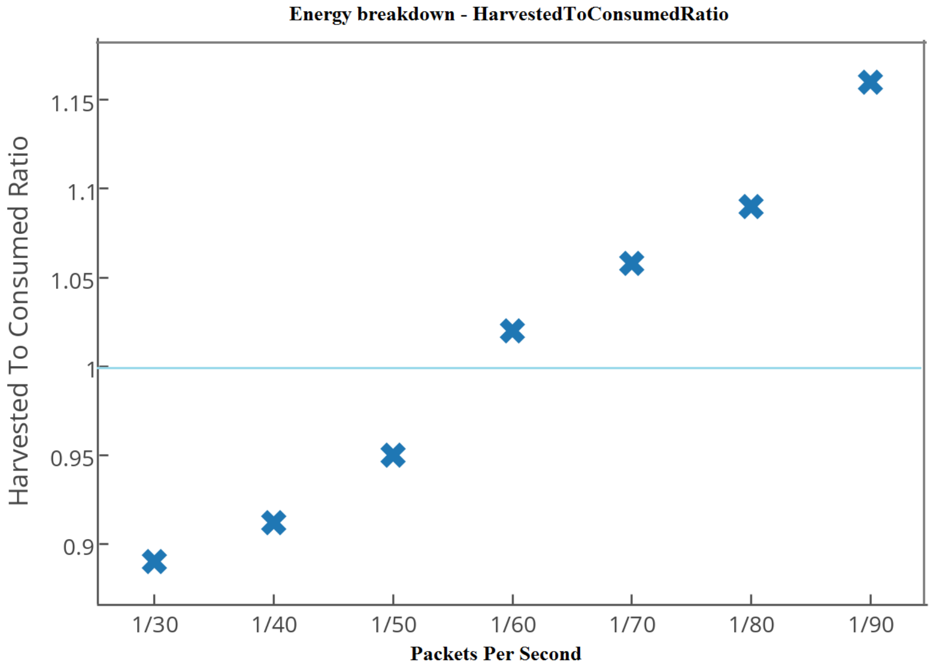


Figure 6.16 *Harvested To Consumed Ratio versus packet rate*

7. CONCLUSION AND FUTURE WORK

Development of radio access protocols for energy harvesting based wireless sensor networks is a new area of research. Due to unpredictable energy arrival process, existing energy-efficient protocols performs poorly in EH-WSN. This thesis work not only explored the existing energy harvesting based MAC and routing protocols but also modified an energy-efficient routing protocol to overcome the energy harvesting process based constraints.

In the beginning of this thesis, a comprehensive survey of the existing energy-efficient and energy-harvesting based MAC and routing protocols is given. This survey highlighted the major benefits and shortcomings of existing radio protocols in literature. The operational limitations introduced by energy harvesting process in sensor networks are also discussed in terms of energy arrival unpredictability, duty cycle of nodes and Energy Neutral Operation (ENO). For uninterrupted function, EH-WSN nodes should maintain ENO state in all cases, where energy harvested is always greater than energy consumed by a node. It is realized that due to energy harvesting constraints, nodes must dynamically adjust their duty cycles as per the traffic requirements. For analyzing the benefits of dynamic or adaptive duty cycle in EH-WSN, adaptive duty cycle enabled T-MAC protocol is simulated against fixed duty cycle enabled S-MAC protocol. The simulation results showcased T-MAC protocol as a better candidate for EH-WSN in terms of data reliability and energy consumption. It also eliminates the hidden node problem with the help of SYNC, RTS and CTS packets.

Due to finite energy in traditional battery-operated WSNs, residual energy of sensor nodes can be easily calculated for making efficient routing decisions. But due to harvesting rate variations in space and time, it is difficult to make routing decisions in multi-hop EH-WSN. Such traits of energy harvesting process discouraged the use of existing routing protocols for EH-WSN operations. Hence, a modified version of Multipath Rings (MPR) routing protocol, called Energy Harvesting based Multipath

Rings (EH-MPR) routing protocol, is proposed for energy harvesting compatibility. It maintains the ENO-state of network nodes and also make the most efficient routing decisions based on energy harvesting rate and residual energy. Eh-MPR routing protocol contains three enhancements; (i) the topology setup phase is revised by implementing a new ring formation scheme for higher data reliability, (ii) controlled flooding of data packets by enabling selective forwarding and finally, (iii) implementation of neighbors' table in sensor nodes with energy harvesting information of their neighbors. To keep the latest energy values in neighbors' table, an energy update packet is broadcasted periodically by all nodes. Using Castalia's realistic wireless channel and radio model, EH-MPR is simulated for low-power, low-data rate and low-bandwidth (1 MHz) networks where satisfactory results are obtained for sub-GHz frequencies (433 MHz and 868 MHz). In the latter part of simulations, EH-MPR routing protocol is compared with the original MPR routing protocol over various metrics of energy consumption and data reliability. In all cases, EH-MPR protocol outperformed MPR protocol and emerged as a better candidate for EH-WSN. It is concluded that although the packet success rate is approximately equal for both protocols, EH-MPR has advantages over original MPR routing protocol in terms of energy cost and uninterrupted operations by maintaining ENO state. At last, the concept of ENO state is explained by plotting energy harvested to energy consumed ratio for multiple packet generation rates. For our simulation parameters, it is concluded that the packet generation rate should be lower than $\frac{1}{60}$ for uninterrupted network operation.

In future, enhancements can be made to optimize this protocol for specific applications. Firstly, property of dynamic energy update can enable the protocol to change the functionalities as per the available energy, thereby enhancing the performance. Secondly, nodes can be enabled with power control which can increase or decrease the coverage area as per the available harvested energy. Lastly, energy predictions for the future energy availability can help in making future routing decisions for energy optimal results.

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