Interference Avoidance Routing for Underwater Wireless Sensor Networks

QUAID-I-AZAM UNIVERSITY
ISLAMABAD

By

Anwar Khan

Department of Electronics
Quaid-i-Azam University, Islamabad.

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Anwar Khan

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Doctor of Philosophy

Department of Electronics
Quaid-i-Azam University
Islamabad, Pakistan

Dedicated to my family

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Student Name: **Mr. Anwar Khan** Signature: ____________

Examination Committee:

a. Prof. Dr. Junaid Mughal Signature: ____________
Department of Electrical Engineering
CIIT, COMSATS Institute of Information Technology
Park Road, Chak Shahzad
Islamabad.

b. Prof. Dr. Muhammad Sher Signature: ____________
Professor/Chairman
Department of Computer Sciences
Faculty of Basic and Applied Sciences
International Islamic University, Islamabad.

c. Dr. Hasan Mahmood Signature: ____________
Associate Professor and Chairman
Department of Electronics
Quaid-i-Azam University, Islamabad.

Supervisor Name: **Dr. Hasan Mahmood** Signature: ____________

Name of Chairman: **Dr. Hasan Mahmood** Signature: ____________

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Dr. Hasan Mahmood
Associate Professor
Department of Electronics
Quaid-i-Azam University,
Islamabad, Pakistan.

Submitted through:

Dr. Hasan Mahmood
Chairman
Department of Electronics
Quaid-i-Azam University,
Islamabad, Pakistan.

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Abstract

Packets routing in underwater wireless sensor networks (UWSN) is challenged by the interference generated during packets forwarding by sensor nodes. The lost packets result in wastage of nodes' battery power in that their retransmission consumes additional power. In order to overcome this challenge, design of interference avoidance routing is one of the promising solutions. Such a routing ensures that the ultimate destination receives packets along the trajectories with the least interference. In this study, three interference avoidance routing protocols: EEIRA (energy efficient interference and route aware), EEIAR (energy efficient interference aware routing) and LF-IEHM (localization-free interference and energy hole minimization), are proposed for UWSN. Network architectures are developed for the deployment of sensor nodes. Classification and review of the novel network, MAC and cross layers protocols are accomplished. The EEIRA protocol involves a unique network architecture and selects the shortest routes with the least interference during packets forwarding towards the ultimate destination. Sensor nodes localization; which involves knowing the three dimensional coordinates of sensor nodes, for the computation of the shortest path in EEIRA is relaxed in EEIAR. The EEIAR also forwards packets along the shortest and the least interference paths using its unique network architecture. However, selection of such paths is based on depth (one dimensional position or single coordinate of the nodes). Localization is difficult to achieve because currents in water make the nodes to change positions. It also consumes extra energy. The LF-IEHM protocol uniquely uses variable transmission range and packet holding time. The variable transmission range avoids the situation when a sensor node does not find any neighbor node for data forwarding that results in packet loss. Also, every node holds a packet for a uniquely chosen packet holding time to minimize simultaneous transmission of packets by sensor nodes. This strategy minimizes interference and the resulting packet loss. Contrary to the conventional approach of route selection that involves coordinates for position specification of nodes, the LF-IEHM uses water pressure a sensor node bears in combination with waiting time to select routing paths. Simulation results reveal that all the three protocols outperform the counterpart schemes in terms of the mentioned performance parameters.

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Chapter 1

Introduction

The inherent quest of the human being for exploring the universe has led to the research and development not only in terrestrial environment but in underwater medium as well. Water constitutes almost 70% of the earth and affects its inhabitants in a direct or indirect fashion. This, in consequence, necessitates the study of underwater environment. Although, the first underwater telephone was made in 1945 during the World War II by the United States navy to communicate with submarines [1], this medium remained unexplored. UWSN has been emerged as a recent field to provide an insight to underwater environment and use it for a number of applications. They include exploring, monitoring and navigating undersea environment, preventing disaster and undersea warfare [2][3][4].

Compared to its terrestrial counterpart, UWSN inherently carries several challenges [4]. The absorption of electromagnetic radiations in water is very significant. The absorption rate at a frequency f in Hz (Hertz) is about $45\sqrt{f}$ dB/km (deciBell per kilometer) [5]. Sea water is conductive to waves only at extra low frequencies in the range $30-300$ Hz. However, large size antennas with high transmit power are required at these frequencies that is impractical. Optical waves also do not work well in water as they are easily scattered and require high precision to point them from source to destination. In essence, acoustic waves are used in UWSN. However, these waves travel at a significantly lower speed (about five-fold slower) in water than radio waves. This brings inherently higher latency in data transfer in underwater networks. The temperature, saline content and pressure of water affect acoustic speed. This further affects the propagation delay and, therefore, affects the underwater communications. With the use of acoustic waves, the available bandwidth reduces and is limited to almost 100 kHz. The presence of marine animals and objects causes connectivity problems and shadow zones in UWSN that results in high bit error rates in packets transmission and reception. Last, but not the least, every node is powered by a finite extent battery and its replacement is an infeasible and costly solution [6]. Because of these challenges, the underwater scenario demands routing protocols specifically designed for it. Consequently, the terrestrial routing protocols cannot be applied to underwater communications.

The conventional routing protocols in UWSN do not take into account the interference associated with the routing trajectories in forwarding packets from source to destination [7][8][9]. These protocols also consume excessive amount of energy due to redundant packets transmission. Although some protocols define restricted forwarding zones to overcome interference [9][10], nodes in these zones die rapidly due to high data load. This badly affects the successful transfer of packets to the ultimate destination. Furthermore, the probability of finding a forwarder node in these zones decreases to a significant extent in situation when the node density of the network is low. Also, defining forwarding zones requires that nodes are aware of the localization (geographical position) of one another that restricts their applicability [11]. It is because in underwater communications, positions of nodes change due to currents in sea. In essence, these protocols suffer from packet loss due to packet collision, interference and inefficient use of finite extent battery power and narrow bandwidth [12].

The design of interference avoidance routing protocols for UWSN is one of the promising ways to combat the interference associated with the routing paths towards destination. These protocols cope with packet loss on account of packet collision and interference. Consequently, the quality of communications is improved, which is always desired, especially in applications when data loss is critical. They include, for instance, military and data sensitive applications such as disaster forecasting (Tsunami, earthquake) and prevention. Interference avoidance also efficiently consumes the finite extent battery power and the narrow bandwidth. When packet loss due to interference is minimized, the power that would otherwise be used for retransmission of the lost packets is saved for sending more packets. This, in turn, not only prolongs the network lifetime but also enhances successful delivery of data packets towards final destination. In addition, with minimized interference, less complex circuitry is required for processing and extracting the received information at the destination.

Interference avoidance routing has been discussed in literature [13]. However, due to the proposed cost function for packets forwarding, nodes closest to the water surface are selected frequently and die soon. This results in packet loss and energy holes (dead nodes) that severely affects system performance at early stage of network operation. Moreover, nodes have to constantly communicate with the sink that not only consumes extra energy but enhances the delay as well. In this thesis, three routing protocols that avoid interference are proposed for UWSN. They are: EEIRA, EEIAR, and LF-IEHM. In EEIRA, a sender node selects a forwarder node that makes the shortest distance towards destination. This strategy ensures that packets reach the water surface with the least number of forwarders. Because the sender decides the forwarder, it also controls forwarding of redundant packets. The choice of forwarder nodes with the least neighbors reduces packet collision, interference and packet loss. This, in turn, minimizes energy consumption and increases the rate with which packets are transferred to the end destination. The EEIAR protocol relaxes the condition of the knowledge of position information of sensors nodes required in EEIRA. In EEIAR, a sender node decides a forwarder node based on the lowest depth and the least number of neighbors. The EEIRA and EEIAR both have unique network architectures to differentiate among source, relay ad destination nodes. The LF-IEHM adjusts the communication (or transmission) range of a sensor node when no sensor node is located within its neighborhood. In such a scenario, the sensor node increases its transmission range and consumes more power to include one or more neighbors. This strategy avoids packet loss. The LF-IEHM also computes packet holding time in a manner to avoid simultaneous transmission of packets by nodes. This ensures reduction in interference, packet collision and, consequently, overcomes packet loss.

The extensive simulations of all the three proposed routing protocols are accomplished using MATLAB. The proposed network is a three dimensional cube in which sensor nodes are randomly deployed. Every node is assigned a unique ID, depth or position coordinates and the initial energy or battery power. The sink node; a principal node usually placed at water surface, gathers packets that nodes transfer to it. The sink then transmits packets to the data center near the water surface. The defined parameters are then used to calculate the performance metrics of the network. They include, for instance, energy consumed by nodes, death of the nodes when their battery power is completely consumed, the number of packets that are dropped during packets forwarding and the number of packets that reach sink. Nodes make use of acoustic links to communicate with one another. The sink makes use of acoustic links for interaction with nodes and radio links to communicate with data center near the water surface.

In all the three proposed protocols, unless stated otherwise, the terms end-to-end delay, delay and network latency carry the same meaning. Similarly, final destination, ultimate destination and end destination are the terms interchangeably used for the sink node. Similarly, the terms nodes and sensor nodes are used interchangeably.

1.1 Thesis Organization

Chapter 2 reviews the current routing protocols for UWSN with their routing mechanism, addressed problems, output results obtained and the cost paid. Chapter 3 provides a thorough analysis of the EEIRA protocol. Chapter 4 deals with the description of the EEIAR protocol.

The LF-IEHM protocol is addressed in Chapter 5. Finally, Chapter 6 arrives at conclusion and mentions the tasks to be accomplished in future.

Chapter 2

Literature Review[1]

2.1 Introduction

This chapter reviews the novel routing protocols for UWSN. The emphasis is given on the routing strategy, addressed problems, merits and demerits of each protocol.

2.2 Challenges in Underwater Communications

2.2.1 Propagation Delay

The radio frequency (RF) waves are significantly attenuated in underwater communications. As a result, underwater communications do not involve the use of RF waves. Rather, they use acoustic waves, which have significantly lower speed than radio waves in water that changes with depth, temperature and saline materials present in sea water [14].

2.2.2 Limited Battery Power

Underwater senor nodes also face the problem of short life due to limited battery power [15]. Replacing the battery of a node is very difficult and counterproductive, particularly at the ocean bed [6]. This limitation demands for efficient and effective use of the electrical power of sensor nodes in UWSN.

[1]The basic idea of the journal paper: Anwar Khan, Ihsan Ali, Abdullah Ghani, Nawsher Khan, Mohammed Alsaqer, Atiqr Ur Rahman, and Hasan Mahmood, "Routing protocols for underwater wireless sensor networks: Taxonomy, research challenges, routing strategies and future directions," *MDPI Sensors*, 18(5): 1619, pp. 1-30, May 2018, bases on the contents of this chapter.

2.2.3 Limited Bandwidth

The harsh underwater medium allows only specific frequencies to carry information [16]. This limits the available bandwidth that, in turn, puts restrictions on the design of the acoustic systems. All the protocols that address issues in transferring packets to the water surface have to keep in view the narrow and limited bandwidth available for underwater communications.

Table 2.1 shows the converge of UWSN with respect to its bandwidth [4].

Table 2.1 Maximum coverable distance with respect to bandwidth.

Converging Limit	Maximum coverable distance[km]	Bandwidth[kHz]
Very long	One hundred	Smaller than unity
Long	Ten to hundred	two to five
Medium	Unity to hundred	Approximately ten
Short	One tenth to unity	twenty to fifty
very short	Smaller than one tenth	Above hundred

2.3 Underwater Routing Protocols

All the designed protocols for UWSN have two categories: full and partial dimensional localization based protocols. They are further described in the lines to follow.

2.4 Full Dimensional Localization based Protocols

Specification of the position of an underwater sensor node requires that the position coordinates of the node are known. Without this information, routing paths are impossible to establish in these protocols. Therefore, these protocols require that the two or three dimensional coordinates information is known. A description of the basic and novel protocols in this category is given below.

2.4.1 VBF and HH-VBF

The vector based forwarding (VBF) addresses the mobility issue of underwater sensor nodes [17]. It predefines a virtual pipe that spans from the transmitter towards the receiver node. Nodes that are locating within the pipe qualify for data forwarding. Every packet contains information about the position of source, forwarder and destination. Reception of a packet makes the receiver to check whether or not it is located within the pipe. If the calculated position is such that it lies within the pipe, the position information is inserted by the node in the packet and sends the packet to next forwarder. Otherwise, the packet is discarded. Since, the protocol limits the number of forwarders in data transmission, it achieves energy efficiency. Also, it is not necessary to know the state information of each node that makes the network easily scalable. However, nodes within the pipe die soon due to frequent selection that creates energy holes and, in turn, results in packet loss. In addition, there may be no forwarder at all within the pipe when the network is sparse. In order to overcome these issues, the protocol analysed in [18] defines the routing pipe for every forwarder node in contrast to the single major pipe in VBF.

2.4.2 DFR

Directional flooding based routing (DFR) considers the link quality to route packets from source to destination [10]. A node sending the packets knows where the receiver and the sink nodes lie. Every node also knows the link quality of its one-hop neighbors. The protocol forwards packets using flooding in a restricted zone formed by the angle among the source, forwarder and the sink. It also ensures that there is at least one forwarder in the flooding zone to avoid packet loss. However, under the worst link conditions, the flooding zone can be extended to include more forwarders and then select the link with the best quality to forward packets. Redundant packets transmission is the major issue with this protocol that unnecessarily consumes the energy of nodes.

2.4.3 FBR

In focused beam routing (FBR) protocol [19], transmission of a control packet is carried out by a source node to nodes that are at one-hop distance from it. This makes these neighbors aware about location information of source and of the final destination. However, not all neighbor nodes respond to the packet. Only neighbors that lie within a cone formed by a certain angle between source and ultimate desired node respond to the packet. Every node calculates its position with respect to the line connecting the source and ultimate desired node to determine whether or not it locates within the cone. A sender node uses many power levels to communicate with its neighbors. It starts with the lowest power level and increases it until it receives replies from the suitable neighbors. When the source node does not get any reply from neighbors even with the maximum power level, it increases the size of the cone to find suitable forwarder nodes. Since relay selection is accomplished within the limited zone, the protocol may not work efficiently in sparse conditions.

2.4.4 REBAR

The protocol [20] establishes a varied radius cylindrical path from source to destination. This path has a lower radius near the sink to involve less number of nodes. This avoids early death of such nodes and achieves energy balancing. The protocol supposes that the knowledge of own position and that of ultimate destination is known to every node. A source node incorporates the information of the established path and its location in the packet and broadcasts it. Upon receiving the packet, a neighbor node calculates the difference between its own distance and the distance of the source from the water surface. If this difference is smaller than a certain limit, it forwards the packet, otherwise drops it. Redundant packets transmission is suppressed by using history buffer. Also, the protocol overcomes the void problem by making nodes near a void to transmit the packets to all its neighbors that are independent of their positions and distances from the sink. Nodes movement with water currents is used as a positive parameter to select different nodes to further achieve energy balancing. Routing in the restricted cylindrical path achieves energy efficiency but compromises the packets that are transferred to the ultimate destination, especially in sparse conditions. Also, significant nodes movement may cause extra amount of energy consumption in position calculation.

2.4.5 SBR-DLP

Routing in this protocol is achieved in sectors and by predicting the location where the destination resides. It makes the destination node mobile rather than fixed at the surface of water [21]. This makes all nodes to know only their positions information and predict the predefined mobility pattern of the destination node. A node does not need to know position information of its neighbors. A node intending to transmit packets broadcasts a control message to its one-hop neighbors that contains its position information and packet ID. Upon receiving the control packet, every neighbor node replies to the source node only if it finds itself nearer to destination (the predefined position of destination) source. The packet collision is overcome by dividing the transmission range of the source node into sectors. Nodes in the sector bisected by the straight line from source to destination are prioritized to send reply to the source nodes. The protocol achieves significant reception of packets at the sink when nodes are mobile. However, it does not take into account the drift in pre-defined position of the destination node.

2.4.6 LASR

The authors in [22] modify the dynamic source routing (DSR) to location aware source routing (LASR) and include two more features. The first feature signifies that nodes are aware of their positions as network topology changes with water currents. The second feature includes link quality to route packets along the paths with minimal noise and interference. However, network conditions may change and the established routes may not remain the same as addressed in source routing. In addition, the LASR assumes that link quality is identical in both directions that may not be true in the hostile underwater communications.

2.4.7 CARP

Basagni and his co-workers propose a channel aware routing protocol (CARP) [23] that keeps in view the successful packets transmission history of nodes to deliver packets from source to destination. It combines hop count with power control strategy to successfully deliver packets and avoid void and shadow zones. However, propagation latency is larger in dense networks where constant checking of packets transmission history introduces the delay.

2.4.8 DUCS

The distributed underwater clustering scheme (DUCS) [24] divides an underwater network into clusters. Every cluster has one major node called a cluster head that receives information from the rest of the one-hop neighbors in the same cluster. It then processes the information to remove redundant data and efficiently transmits the desired data to the sink using other cluster heads. A cluster head transfers the information of a node in one cluster to a node in another cluster. It achieves energy efficiency by reducing the number of control messages among sensor nodes through the cluster head. It also leads to high packet delivery ratio. However, the movement of nodes with water currents seriously degrades the performance of the system. In addition, the cluster head is overloaded and it depletes of energy rapidly that creates void holes in the network and degrades its performance.

2.4.9 QERP

The authors in [25] propose a quality-of-service (QoS) aware evolutionary cluster based routing protocol (QERP) to mitigate the adverse channel effects in underwater communications. The protocol uses the genetic algorithm and divides the network into clusters and specifies the cluster heads and the routing paths from the routing tables that nodes share with one another. Transferring packets to water surface, propagation latency and consumption of energy are improved. However, the load on the cluster heads makes them depleted of energy at the early stage that creates energy holes in the network and degrades system performance.

2.4.10 RIAR

Majid and his colleagues propose a reliable and interference aware protocol to mitigate the unwanted link effects while transferring data to ultimate destination [13]. The choice of a relay, achieved by a node ready for data transmission, is accomplished on the bases of its number of hops from the surface sink, neighbors and the greatest distance from source to the relay node. These parameters are combined to propose a cost function. A relay node with the highest value of the cost function is the suitable candidate for data forwarding. The protocol performs well in sparse networks in terms of throughput, consumption of energy and latency. However, it causes early death of nodes closest to the water surface that reduces the throughput.

2.4.11 MC

The protocol in [26] achieves the maximum coverage (MC) of the network in terms of data gathering from sensor nodes using two mobile sinks. The mobility of the sinks in a circular fashion ensures consumption of energy of nodes in a balanced manner and reduces packet loss. However, rather than moving to the targeted locations, where nodes have data to send, the sinks follow the predefined circular paths. This leads to dropping out of some packets and increases the delay, especially in sparse conditions.

2.4.12 BEEC

The balanced energy efficient circular (BEEC) routing protocol [27] considers a circular network divided into ten circular regions called sectors. Two mobile sinks collect data from these sectors; one sink for five different sectors. The sinks move in a circular pattern to gather data from source nodes. This reduces and balances energy consumption of nodes and enhances packets that are transferred to end destination. However, nodes ready to participate in data transmission are not given priority, rather they have to wait for the sinks, which follow a fixed pattern of movements independent of the network conditions that leads to packet loss and delay. Also, the protocol performs poorly in sparse conditions.

2.4.13 SMIC

This protocol inserts mobility to the sink and further adds incremental relaying to perform routing in a cooperative manner [28]. The relay is selected based on its residual energy, depth and the quality of the link. A mobile sink gathers data packets from nodes. Improved performance is shown in transferring packets to the end destination and longer lifetime of the network. However, when the network density is low, the sink mobility results in significant expenditure of energy, packet loss and latency.

2.4.14 VBF, HH-VBF and FBR

The authors in [29] perform a comparative study of the VBF, HH-VBF and FBR protocols. They conclude that for the selected underwater scenario, VBF has the longest propagation latency and network lifetime. Conversely, packets that are transferred to the end destination are the highest in number in HH-VBF with the correspondingly shortest life span of the network.

2.4.15 MEES

The mobile energy efficient square (MEES) routing protocol uses two mobile sinks at the longest possible distance from each other [30]. Their movements follow predefined linear paths to collect data from nodes. The protocol improves throughput, energy consumption and network lifetime. However, rather than moving to the locations where nodes have data ready for transmission, the sinks follow predefined paths that causes packet loss and delay. In addition, nodes drop packets when the sinks are not within their communication range. Furthermore, the network performance is poor in sparse conditions.

2.4.16 AVN-AHH-VBF

This protocol avoids a void node by adaptively using the HHVBF protocol. It improves the VBF protocol in three ways [31]. Firstly, every node forwards a packet only if the next hop is not a void region. A void region is the one where only one neighbor exists for the source node. In this case, the source node discards packets and does not forward them further to reduce energy consumption. Secondly, the depth of a relay node in the pipeline is also taken into account to receive packets from a source node and forward them to the sink. This brings reduction in propagation latency. Thirdly, the holding time considers the number of hops a packet passes through and nodes residing in the vicinity. This results in reduction in delay.

However, the protocol reduces energy consumption at the expense of packet loss. It also suffers from the major problem with VBF; poor performance in sparse conditions.

2.4.17 BEAR

The balanced energy adaptive routing (BEAR) protocol considers a hemispherical network and divides it into sectors of equal radii [32]. Nodes that reside closer to the sink are assigned more power because of greater data load on them than the farther nodes. In addition, the density of nodes is kept higher near the sink than the rest of the network. Every node in a sector selects a forwarder node in the sector above it until data packets reach the sink. The protocol balances energy consumption and, therefore, prolongs the network lifetime.

2.4.18 Hydrocast

In hydrocast, sensor nodes use water pressure in an opportunistic fashion for transferring packets to the end destination [33]. The selected set of forwarder nodes maximizes routing in the greedy manner and reduces interference. A dead and recovery method is also proposed to ensure that packets reach to the destination. The protocol achieves energy balancing, high packets reception at end destination and low latency. However, in sparse conditions, the dead and recovery method does not perform well as nodes do not find enough neighbors. This compromises the performance of the proposed scheme.

2.4.19 OVAR

The opportunistic void avoidance routing (OVAR) protocol uses opportunistic routing to address the void problem [34]. In OVAR, every node is capable of adjusting its number of neighbor nodes in the forwarder set to transmit data to destination. The forwarder set is selected for a node by making use of the probability a packet will be delivered and advanced. The protocol shows improved performance in energy expenditure, latency in propagation and throughput. However, it involves unbalanced energy consumption as nodes near water surface are frequently selected for data forwarding.

2.4.20 GEDAR

The scheme proposed in [35] makes use of geographical opportunistic routing in combination with adaptively changing the depth. The protocol forwards packets from source to destination in a greedy and opportunistic fashion. A source node selects the set of forwarding nodes based on packet advancement. The packet advancement is obtained by subtracting the distance between a neighbor node and destination from the mutual separation between source and the selected destination. In the recovery mode, when a node finds itself in the void region (has no neighbors at all), it informs its two-hop neighbors. Using this information, it decides the new depth location to avoid the void zone. The selection of forwarder set can be done at the source, relay or receiver side. Furthermore, the coordination methods among the forwarder nodes are either timer based or control packet based. The latter, however, leads to energy consumption, especially in sparse conditions.

2.4.21 EGRCs

An energy-efficient grid routing based on 3D cubes (EGRCs) protocol to address the inherent challenging properties of the underwater medium is proposed in [36]. The entire network is considered as a cube that is further divided into smaller cubes called clusters. A cluster head is selected based on its residual energy and location information. Every cluster head further selects a relay node based on residual energy, propagation latency and location. The protocol improves energy expenditure, propagation latency and throughput. However, death of a cluster head severely degrades system performance.

2.4.22 MDA-SL

A message dissemination approach for storage limited (MDA-SL) UWSN involving opportunistic routing is proposed in [37] to track underwater objects. The scheme evaluates the messages received by the nodes to forward or discard packets. Data packets are forwarded towards nodes with high mobility or residual energy. When memory elements of nodes are full, all newer messages are discarded. In this way, the throughput is optimized. However, nodes with high mobility and residual energy die rapidly due to overloading that creates energy holes in the network. In addition, packets are lost when the storage elements of nodes are full.

2.4.23 NEFP

The novel efficient forwarding protocol (NEFP) performs three tasks: defines the routing zone to avoid unnecessary forwarding, calculates holding time to avoid packet collision and uses Markov chains to estimate the forwarding probability of packets in the varying topology [38]. However, it misperforms when network density is low, when the probability of forwarding a packet reduces fairly as forwarders are less likely to find in the defined forwarding zones.

2.4.24 TC-VBF

The topology control VBF (TC-VBF) addresses the issue of nodes' communications in sparse conditions and selects forwarders in the manner of VBF but according to the density of the network [39]. However, it suffers from the same problems and issues as VBF, described above.

2.4.25 NGF

The new greedy forwarding (NGF) protocol divides the number of packets to transmit among the forwarding nodes if more than two forwarders are involved to forward packets [40]. The division involves Chinese remainder theorem. This reduces the overall routing load per node and achieves energy balancing that, in consequence, increases the network lifetime. However, it introduces unnecessary end-to-end delay when packets are sent to many nodes.

2.4.26 LOTUS

The range-based low-overhead localization technique (LOTUS) relaxes the condition of using four sensor nodes as reference nodes to accomplish the localization of nodes [41]. It uses two reference nodes to localize nodes. This relaxation is helpful in identifying the position information of nodes in sparse conditions. However, with two reference nodes, the probability of error in position estimation of nodes increases.

Table 2.2 Full dimensional localization based routing protocols.

Protocol	Routing Strategy	Problem Addressed	Merits	Demerits	Year
VBF	Selects forwarder nodes within a pipe from source to destination	Nodes' mobility	Energy efficiency	Low throughput in sparse conditions	2006
HH-VBF	Rather than defining a single routing pipe as in VBF, a separate pipe is defined for every forwarder node	Nodes' mobility	Scalability, low packet drop in sparse conditions	High overhead, pipe size sensitive routing	2007

DFR	Defines a restricted forwarding zone formed by the angle among source, relay and destination nodes	Nodes' mobility	Scalability, low packet drop in sparse conditions	High overhead, pipe size sensitive routing	2007
FBR	Selects relays within a cone formed from source to destination	Energy consumption	Energy efficiency and low latency	Low throughput in sparse conditions	2008
REBAR	Creates an adaptive cylindrical path from source to destination with varied radius to choose forwarders	Energy consumption and early death of nodes close to water surface	Energy efficiency and void hole control	Error in position calculation of nodes with movements	2007
SBR-DLP	Estimates position of mobile destination nodes	Nodes mobility	Energy balancing	Error in estimation of destination position, significant nodes mobility may affect data rate	2009
LASR	Packets are forwarded along the routes with minimal noise and interference	Nodes mobility and link state conditions	High throughput	Latency in updating routes information leads to false forwarder positions estimation	2006
CARP	Uses power control and successful packets transmission history of nodes	Void and shadow zones	High throughput, Small utilization of energy and low delay	Propagation latency in dense conditions due to constantly checking of successful packet transmission history	2015
DUCS	Divides the network into clusters with a cluster head in every cluster that forwards packets of other nodes to the sink	Increased energy utilization on account of messages exchange	High packet delivery, energy efficiency	Nodes mobility and death of cluster nodes severely degrade system performance	2007
QERP	Uses the genetic algorithm to divide the network into clusters and cluster heads for data forwarding	Severe channel conditions	High packet delivery ratio, energy efficiency and low packet latency	Cluster heads are overloaded and die early that causes energy holes	2017

RIAR	Selects a forwarder using its separation from upper surface, source node and number of neighbors	Adverse channel effects, void zone	Reliability, energy efficiency	Early death of sensor nodes close to water surface	2016
MC	Two sinks moving in a circular fashion get data from source nodes	Energy consumption	Balanced energy consumption, low end-to-end delay, high throughput	The merits are compromised in sparse conditions	2016
BEEC	Two mobile sinks collect data from source nodes in a circular network	Energy consumption	Balanced and low energy consumption, high throughput	Sinks don't first move to locations on priority where nodes have data to send that causes packet loss, poor performance in sparse conditions	2016
SMIC	Uses incremental amplify and forward cooperative routing methods	Adverse channel conditions	High throughput	Poor performance when network is sparse	2016
VBF, HH-VBF and FBR	Performs relative comparison of VBF, HH-VBF and FBR	Throughput and energy consumption	Longest network lifetime in VBF and highest throughput in HH-VBF	Longest end-to-end delay in VBF and shortest network lifetime in HH-VBF	2017
MEES	Two mobile sinks located at the farthest distance move in predefined linear paths to collect data from nodes	Energy consumption	Energy efficiency, energy balancing	The sinks don't move in priority to locations where nodes have data to send, nodes drop packets when the sinks are not in their communication range	2017
AVN-AHH-VBF	Improves VBF by considering void region, depth and altering holding time	Void region, energy consumption	Energy efficiency	High packet loss to save energy and poor performance in sparse conditions	2016
BEAR	High energy nodes in greater density closer to the sink are selected	Energy balancing	Long network lifetime, balanced energy consumption	Poor performance in sparse conditions	2016

Hydro-cast	Pressure based opportunistic routing with dead and recovery method to ensure packets are sent to destination	Interference, energy consumption	Energy efficiency	Compromised performance in sparse conditions	2016
OVAR	Uses opportunistic routing and selects relay nodes based on packet delivery probability and packet advancement	Void zone	Energy efficiency, high throughput, low end-to-end delay	Unbalanced energy consumption	2016
GEDAR	Uses opportunistic routing and selects forwarder nodes based on packet advancement	Energy consumption, void zone	Energy efficiency	Unbalanced energy consumption	2016
EGRCs	A 3D cube network is sub-divided into cubic clusters with cluster head selected in each cluster based on residual energy and position while relay nodes selected based on residual energy, position and end-to-end delay	Medium properties	Energy efficiency, low end-to-end delay, high throughput	Degraded performance when cluster head dies	2016
MDA-SL	Messages forwarded to high mobility or residual energy nodes are evaluated to decide forwarders	Tracking underwater objects	High throughput	Unbalanced energy consumption	2016
NEFP	Combines forwarding probability of a packet with packet holding time in a routing zone formed by the angle among source, forwarder and destination	Nodes movement	Energy efficiency	Compromised performance in sparse conditions	2016

TC-VBF	Modifies the VBF protocol to select forwarders in response to nodes' density	Nodes' Movement	Energy Efficiency	Low throughput when number of nodes is small	2017
NGF	Divides the packets between two or more nodes based on Chinese remainder theorem	Load per node	Eenergy balancing	High end-to-end delay	2016
LOTUS	Uses two instead of four reference nodes to position sensor nodes	Localization	Efficient energy expenditure and low delay	Greater probability of error in position estimation of nodes	2016

2.5 Other Localization based Routing Protocols

The authors in [42] propose a routing protocol that overcomes energy and coverage holes. When the residual energy of a node falls below a certain threshold, it broadcasts its status to the neighbors nodes. All the nodes receiving the broadcast message further forward the message. Other nodes then move to the position of the node with energy lower than the threshold. Movement of nodes is controlled in a manner that new holes are not created in response to covering the already created holes. However, it exhibits compromised performance when the network density is low and nodes do not have enough neighbors to communicate with them.

The authors in [43] propose a routing scheme using Markov model to select routes from bottom to top that are more stable, adaptable with respect to the varying data traffic and have less number of hops. However, changes in positions of nodes due to currents in sea may lead to false position computation of a relay.

Waheed and his colleagues design a self-organizing protocol where every node forwards the data packets of nodes above it towards the gateway in the radial network [44]. A control packet is broadcasted by a gateway. Once the neighbors respond, the gateway sends a route request to the neighbors that process it until the last node sends an acknowledgement to the gateway. This information is used by the gateway to construct strings that forward the data packets. This process reduces the propagation latency and increases the throughput. However, the protocol suffers from void problems when a node in the string dies that results in packet loss. Also, the mobility of nodes does not make it easy to form strings of nodes and forward the packets in a smooth manner.

Mobility patterns for the gliders to avoid void zones is proposed in [45]. From the predefined positions of the gliders at the start of the sojourn tour, the direction of motion, current positions and distance from the neighbor gliders and the mobility patterns are defined and estimated, so no void zone is left. The transmit power of the gliders is also varied in the defined mobility patterns. However, the mobility model consumes too much energy of the gliders in sparse conditions.

The authors in [46] argue that localization is beneficial in dynamic underwater networks where nodes frequently change their positions. However, at the same time, knowing the localization information by nodes is ineffective in some proposed cases.

2.6 Partial Localization based Protocols

Instead of the three dimensional position information of sensor nodes, these protocols require only their one dimensional position information. Because of this, they are also called localization free protocols. The one dimensional position information is often the depth of sensor nodes or some measure of it. These protocols are described in the lines to follow.

2.6.1 DBR

This protocol makes routing based on depth (DBR) and is the pioneering one in transformation from localization based to localization free routing in UWSN [7]. The DBR deploys multiple static sinks at the surface of water and two source nodes at the bottom of the network. Source nodes sense the desired attribute and forward the data packets towards the sink in a flooding manner. Every node inserts its depth and ID information in the data packets to send. Upon receiving a data packet, every node holds it until the holding time. A forwarder node forwards a received packet if it comes from a higher depth node, otherwise discards it. The DBR has improved transfer of packets to end destination with low latency due to selection of nodes with the lowest depth as relays. However, it transmits a same packet multiple times and has high load on the nodes close to the sinks (low depth). Such nodes die soon and create energy holes in the network. These holes affect the system performance in later stage of network operation.

2.6.2 EEDBR

This protocol introduces the concept of energy efficiency to DBR (EEDBR). It combines nodes that have high power left in thier batteries in addition to being the low depth nodes. This counteracts the effect of rapid death of low depth nodes in DBR [47]. When a sender node has to select a forwarder node, it selects a forwarder that has the highest battery power left and is nearest to water surface. This leads to energy balancing and avoids energy holes in the network. However, the EEDBR does not guarantee reliability of data at the final destination. It is because only a sender node decides the next forwarder in EEDBR that may increase the probability of packet loss if the link quality is not good.

2.6.3 ODBR

The optimized depth based routing (ODBR) protocol [48] assigns initial energy to nodes based on their vertical distances (depth) from the surface of water. Nodes closer to the water surface are, therefore, assigned more energy than nodes farther from it. This results in balanced consumption of energy and prolongs the network lifetime. However, this protocol only works in shallow water zones. It does not perform well in networks that require deployment of sensor nodes at the bottom of ocean as such nodes are assigned the least amount of energy.

2.6.4 DEAC

This protocol has awareness about depth and energy of nodes and performs routing in a cooperative fashion to avoid data corruption by the underwater medium [49]. The protocol adaptively selects a depth threshold for a source node using its existing neighbors. Following this, a relay node is selected making use of its battery level, existing neighbors and condition of the link. The destination node is selected out of the depth threshold. The protocol performs well in terms of transferring packets to the end destination. However, it is energy inefficient due to cooperative routing.

2.6.5 EBECRP

The authors in [50] combine energy efficiency and energy balancing with the concept of clustering to route data. It divides the network into sectors. Each sector is assigned a cluster head to collect data from its neighbors and reduce multi-hoping. Two mobile sinks monitor the dense and sparse regions of the network based on the number of neighbor nodes. Nodes either send the data to the sinks or to the cluster heads. The sinks then collect the data from the cluster heads. The protocol prolongs the network lifetime by reducing energy consumption. However, the cluster heads are overloaded and die rapidly that causes packet loss. Also, the movement of cluster heads with water currents is a major issue that leads to packet loss.

2.6.6 DRADS

The depth and reliability aware delay sensitive (DRADS) protocol modifies the concept of opportunistic routing [51]. It considers the depth information in addition to the link state information when a forwarder sends packets to the sink. This reduces energy consumption and increases the throughput. However, the load on low depth nodes increases and they die soon deteriorating the system performance.

2.6.7 DBR-MAC

In DBR-MAC protocol [52], low depth nodes that suffer from high data load are prioritized to access the channel. The angle, depth and overhead of the neighbor nodes are considered for the low depth nodes to make them access the channel preferably than the rest of the nodes. This leads to improvement in energy expenditure, throughput and latency. However, prioritizing the low depth nodes overburdens them and they die in a rapid fashion. This creates energy holes in the network that leads to packet loss in the subsequent operation time of the network.

2.6.8 E-CARP

The authors in [53] improve the CARP protocol and make it localization free and more intelligent in selecting relay nodes. It routes packets in a greedy hop-by-hop manner and relay nodes are selected when the network conditions are steady. Energy consumption and network lifetime are improved at the price of high latency due to waiting for steady conditions.

2.6.9 DSRP

Akanksha and his colleagues investigate the effect of mobility of nodes on distributed delay sensitive routing protocol (DSRP) [54]. They consider the random Waypoint model. This model involves changes in position and velocity of the sensor nodes to move to a new destination. At each destination, nodes stop momentarily and then move to new positions. The proposed routing strategy involves the movement style of nodes, the expected traffic along the chosen paths and the localization of nodes. The speed with which nodes move is kept between the maximum and minimum values. The conditions of no mobility, low mobility and high mobility of nodes are compared. Based on simulation results, the proposed protocol shows that high mobility nodes have the greatest throughput at the price of the highest expenditure of energy and latency.

2.6.10 DBR-NC

The depth based routing network coding (DBR-NC) improves the energy cost of packets transmission, delay and packets reliability in the original DBR scheme. The network coding takes into account the adverse channel effects to ensure reliability. However, the protocol assumes an ideal MAC layer compared to the realistic MAC layer in DBR [55].

2.6.11 EBPR

The energy balanced pressure routing (EBPR) uses the feedback from sensor nodes for the beacon signals to avoid void zones [56]. It does not take into account the velocity of nodes to avoid void zones. In addition, residual energy is considered as a routing metric in selecting a forwarder node. Furthermore, the proposed protocol uses the redundant route information to help nodes that do not have this information to update route information. The EBPR increases the lifetime of the network. However, it suffers from the poor performance in sparse networks when sending beacon signals is less effective.

Table 2.3 Partial localization based routing protocols.

Protocol	Routing Strategy	Problem Addressed	Merits	Demerits	Year
DBR	Uses lowest depth sensor nodes from bottom to top to forward packets in a flooding manner	Localization	High throughput and relaxes the requirement of full dimensional position information of sensor nodes	High energy consumption and early death of low depth nodes	2008
EEDBR	A sender node decides the forwarder based on depth and residual energy	Energy balancing and death of low depth nodes	Balanced energy consumption and death of low depth nodes	Low reliability of packets delivery	2012
ODBR	Assigns more energy to nodes closer to water surface	Energy balancing, early death of nodes closer to water surface	Long network lifetime, balanced energy consumption	Does not work in deep water zones where bottom nodes should have enough energy to sense attribute	2016
DEAC	Uses cooperative communications to avoid data corruption by channel	Adverse channel effects	Reliability and high throughput	High energy consumption	2016

EBECRP	Uses clusters and two mobile sinks to collect data from nodes	Unbalanced energy consumption	Energy efficiency and balancing	Death or movements of cluster heads results in packet loss	2016
DRADS	Considers the depth of the forwarders in addition to the links state	Reliability, energy consumption	High throughput, low end-to-end delay and energy efficiency	Early death of low depth nodes	2016
DBR-MAC	Prioritizes forwarder nodes closer to the sink based on depth, angle and overhead	Medium access	Energy efficiency, high throughput	Unbalanced energy consumption	2016
E-CARP	Hope-by-hop forwarder selection in a greedy manner is accomplished when the network conditions are steady	Energy usage	Efficient energy usage and delay	High end-to-end delay due to waiting for the channel conditions to become steady before selecting the relay nodes	2016
DSRP	Nodes' position and velocity changes are used to deliver packets to the surface sink	Mobility	High throughput	Inefficient energy utilization and delay	2016
DBR-NC	Combines network coding with DBR	Adverse channel conditions	Energy efficiency, high throughput and low end-to-end delay	Idealized and too much simplified MAC layer	2016
EBPR	Feedback from the sensor nodes based on beacon signals and their residual energy is used to route data	Void zone	Energy efficiency	Compromised performance in spare conditions where beacon signals do not work effectively	2016

2.7 Lessons Learned

Routing protocols for UWSN are classified into two classes: protocols that require the full dimensional localization and partial localization information. The former class requires that the two or three dimensional position coordinates information are known to in order to construct the routing strategies. These protocols can be used to precisely know the position of targets such as submarines. However, localization is a challenging task. On the other hand, protocols that require the partial localization information use the depth of the sensor nodes in constructing the routing paths. These protocols are used for applications where scalability is required or when knowing the position information of nodes is not important such as underwater environmental monitoring. Both types of the protocols are further used to address the problems and issues associated with underwater environment as described above.

This chapter classifies the routing protocols for UWSN into full dimensional and partial localization based routing protocols. The problems that these protocols address and the cost paid for addressing the problems are described. The full dimensional routing protocols require the two or three dimensional position information of underwater nodes. This requirement is very challenging in underwater communications as nodes are moved by currents. The partial localization based routing protocols require only the depth information (one dimensional information). This is easily acquired by adding a pressure sensing circuitry to the sensor nodes.

Chapter 3

EEIRA: Energy Efficient Interference and Route Aware Protocol for UWSN[1]

3.1 Introduction

The UWSN is one of the emerging disciplines for academic and industrial research due to its capability of affecting the human being directly or indirectly. It has been successfully applied to accomplish several applications as mentioned in [2][3][4]. These applications necessitate addressing the research challenges inherently associated with such networks. For instance, water significantly absorbs the radio frequency waves [5]. The absorption rate increases as the frequency of the these waves increases. Therefore, underwater communications do not make use of the radio waves, rather acoustic signals are used. However, compared to a radio wave speed, acoustic speed is five order slower in water. This enhances the propagation latency in underwater networks. In addition, speed of acoustic signals in water changes with water pressure, saline content present in sea water, its temperature and density. This bends the traveling path of the acoustic waves and disables the nodes to hear one another [5].

Underwater nodes are powered by batteries that have short lifetime and replacing them is generally not feasible, especially at the bottom of ocean [6]. Batter power is consumed inefficiently when scattering of acoustic energy takes place in water. This makes energy efficient and interference avoidance protocol design as one of the potent strategies for UWSN to optimally utilize the energy of nodes.

[1]The basic idea of the journal paper: Anwar Khan, Mohammad Hossein Anisi, Ihsan Ali, Nadeem Javaid, Muhamamad Qaisar Azeem, and Hasan Mahmood, "An energy efficient interference and route aware protocol for underwater wireless sensor networks," *Ad Hoc & Sensor Wireless Networks (AHSWN)*, Vol. 41, No. 1-2, pp. 31-53, May 2018, bases on the contents of this chapter.

In localization free protocols for UWSN [7][9], forwarding of redundant packets is the major problem. Although, packet holding time function and history buffer are introduced in [7] to avoid it, all forwarder nodes still forward a single packet when it comes from a lower depth node. Consequently, energy is consumed in unnecessary packets forwarding that shortens the lifetime of sensor nodes. It also leads to packet collision and interference that ultimately contribute to packet loss. This phenomenon is more obvious when the number of sinks reduces. In addition, these protocols have degraded performance in dense network conditions when interference prevails. In contrary, protocols that involve localization define restricted regions for selecting forwarder nodes [10][17][18]. However, it increases the probability of packet drop when forwarder nodes are not available within these regions. The involvement of route finding strategy further increases delay and energy consumption [19]. Also, both types of protocols consider nodes close to the water surface for data forwarding that overburdens such nodes and they die rapidly. Death of such nodes leads to packet loss. In essence, energy is unnecessarily consumed by forwarding redundant packets in these protocols. This consumes the energy inefficiently and causes interference.

The EEIRA protocol is presented in this chapter for UWSN. This work extends our work in [57] that investigates the choice of the best relay. A best relay node has the least number of neighbors and connects with the destination using shortest path of the available paths. The choice of relay node is accomplished using a source node full communication range so that the probability of packet drop due to the unavailability of relays fairly reduces. Also, a sender node decides the next forwarder node so that the redundant packets problem is resolved. The choice of relay nodes with smallest count of neighbors overcomes interference and reduces packet loss and collision. The shortest path choice ensures the least number of intermediate relay nodes towards destination. This, in turn, not only reduces end-to-end delay but also saves energy. When the best relay nodes die, other relay nodes that satisfy the forwarding criteria are selected as the best relays.

3.2 Related Work

The anaycast scheme presented in [33] combines opportunistic routing using water pressure on nodes (hydrocast). A strategy of recovery of packets is presented when nodes are dead. Packets are advanced opportunistically to maximize the greedy process of data forwarding. The proposed technique has superior performance as compared to the counterpart schemes in reducing co-channel interference. The proposed scheme is also more energy efficient than DBR. However, its performance degrades when network density is low and in the absence of recovery method.

The concept of replacement of the sensor nodes along with energy efficient routing strategies is addressed in [59] to monitor underwater oil reservoirs during earthquake. Since nodes have significantly smaller lifetime than the monitoring time, replacing nodes and using the proposed routing scheme provides uninterrupted monitoring. However, the proposed scheme mainly considers ways to reduce replacement cost of the nodes. In addition, the scheme exhibits poor performance as the size of the network grows. Yang and his co-workers propose a routing protocol that finds a routing path with the smallest delay from source to destination [60]. A broadcast message informs other nodes about the selected route for data forwarding. The protocol achieves energy efficiency but leads to extra delay when nodes are informed about the selected smallest delay path.

The routing protocol proposed in [61] makes use of the geographic information of nodes and partial network coding (GPNS). The scheme improves energy expenditure, latency and throughput. However, its working is compromised when the number of encoded packets increases beyond a certain threshold. The reason is that partial network coding encodes the packets randomly that enhances the probability to encode and decode a single packet a number of times. This enhances the delay when the number of packets increases. Ghoreyshi and his co-workers propose a routing protocol that selects relay nodes in an opportunistic manner using localization of nodes [62]. The localization is obtained using periodic beacon signals. This information is then utilized to avoid the paths where forwarders are not available. As a result, energy usage, delay and data loss is overcome. However, nodes nearest to the water surface are overburdened that makes the network less stable.

Aiming for minimizing energy expenditure, proposition of two protocols is given in [63]. In one scheme, forwarding of data packets directly towards destination is avoided. The second protocol introduces a depth threshold to the first for minimizing the hops among nodes. The proposed schemes make the network division into circular rings, termed as sectors. However, these schemes exhibit poor performance as the radius is varied. The scheme presented in [64] use autonomous underwater vehicle (AUV) for efficiently collecting data (AEDG). The sensor nodes forward data to gateways. The data collection from the gateways is accomplished by the AUV using the shortest path. In order to avoid overloading of gateways, every gateway collects data from a limited number of nodes. The movement of gateways depends upon network density. Both the schemes achieve energy efficiency and balancing at the expense of high latency.

A cooperative routing based energy efficient protocol by moving the sink in elliptical and straight paths is proposed in [65]. The protocol has superior performance in comparison to the counterpart techniques in energy expenditure and throughput. However, the energy expenditure enhances as the network operates for long time. The scheme designed by

Khan and his co-workers [66] ensures that relay nodes residing in the center of network are assigned greater priority values for data forwarding towards the surface of water. The protocol results in reduction in energy expenditure and latency. However, relay nodes in the center of network die fast due to overloading by data traffic. The authors in [67] modify the DBR by reducing its energy expenditure. However, redundant packets is still an issue in the improved version that results in packet collision and interference. A routing algorithm inspired by the ultrasonic frog during matting is addressed in [68] for relay selection. Nodes deployment in the proposed network is random. The sensor nodes having the lowest energy are kept in the worst places of the network where data traffic is the lowest. The protocol ensures energy efficiency but still has the issue of packet collision as the number of nodes increases.

3.3 Channel Model

The channel model used is the same as in [57]. This includes modeling of noise and losses along the channel. It also includes variable acoustic speed along the channel.

3.4 The Proposed Protocol

3.4.1 Network Setup and Nodes Deployment

The network consists of randomly placed nodes submerged in an underwater zone of dimensions $500m \times 500m \times 500m$ as depicted in Fig. 3.1. On the water surface at network top, the sink is mounted. To distinguish among nodes, network total depth D is split into three zones. The depth of the top region is confined to $0m < D \leq 150m$ and is called destination region. The corresponding nodes are called destination nodes (being closed to the sink (destination)). The condition $150m < D \leq 350m$ defines the mid region with nodes called relay nodes. The bottom nodes are named source nodes and are characterized by $350m < D \leq 500m$. All the sensor nodes have limited energy except the sink. All the nodes are equally capable of sensing the desired attribute. Data forwarder nodes are selected using neighbors density and span of the path. A node that offers shortest distance towards the destination with the lowest count of neighbors is picked as the best relay. In Fig. 3.1, node F is the best relay for source node A. Node H is the best relay for node F. In a similar fashion, destination node J is the best relay node for node H. The next section describes the criteria of selection of a node as the best relay.

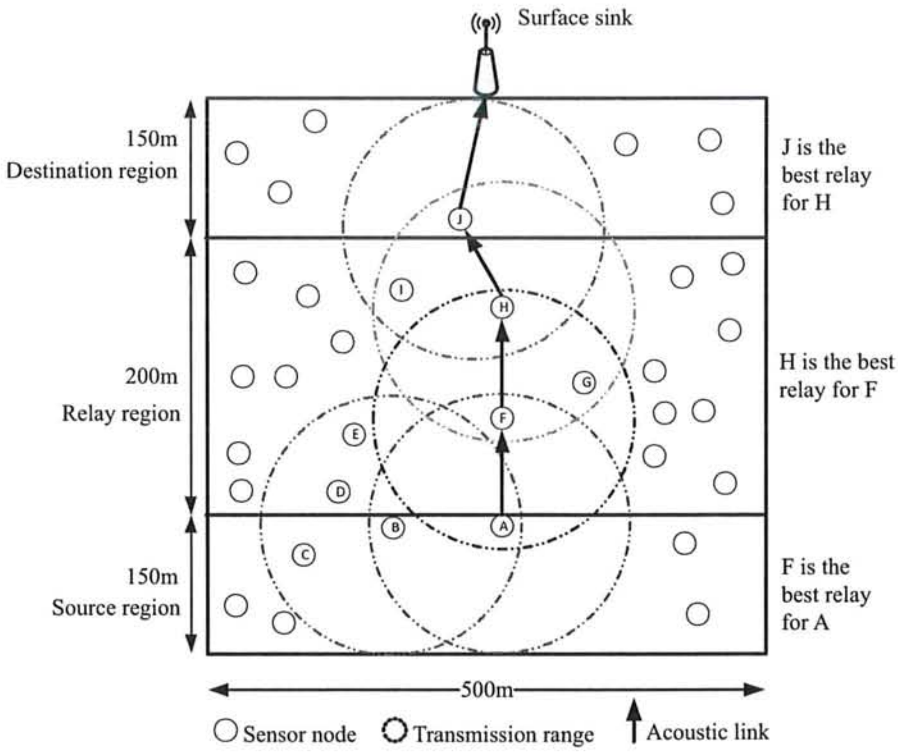

Figure 3.1 Network architecture.

3.4.2 Network Setup and Neighbor Identification

After deployment, nodes exchange hello packets through broadcasting. The distinct ID and position of a node are embedded in the hello packet that it broadcasts. Every node has awareness of own and end destination positions [19]. Every node waits for sometime to hear from its one-hop neighbors. The waiting time is dependent on the time consumed in propagation and processing of data packets. Upon hearing a neighbor back, a node creates a routing table and embeds neighbor ID in it. This process is done for all neighbor nodes. The sensor node then broadcasts its routing table. Every node performs this procedure so that awareness about neighbors is obtained. If a node receives no response from its neighborhood within waiting time, it broadcasts the hello packet again. It declares no neighbor at all when it does not hear from any node in vicinity after the specified waiting time. Sensor nodes periodically exchange hello packets to know about the number of neighbors and position information because currents in water change locations of nodes.

3.4.3 The Best Relay Selection

The selection of the best relay involves a node that is located in such a way that its distance towards the destination is the shortest and it has the lowest count of neighbors. The shortest distance minimizes end-to-end delay so data packets reach to destination in the least possible time. The least number of neighbors ensures selection of the least interference path. When a sensor node, having sink not in its transmission range, has to send data, it always chooses the best relay to forward data.

The Euclidean distance $d_{i,j}$ connecting a source node i having coordinates (x_i, y_i, z_i) with a relay node j with coordinates (x_j, y_j, z_j) is calculated by

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \tag{3.1}$$

Proceeding as the same, the Euclidean distance $d_{j,k}$ connecting the relay with a destination k having coordinates (x_k, y_k, z_k) is given by

$$d_{j,k} = \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2 + (z_j - z_k)^2}, \tag{3.2}$$

the computation of the shortest distance, SD, towards the source is as follow

$$SD = min(d_{i,j} + d_{j,k}). \tag{3.3}$$

For neighbor calculation, the relay node j is in vicinity of source i if it locates inside the communication range R_i of i, which is given by

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \leq R_i. \tag{3.4}$$

If N_j is set of nodes in vicinity of the relay node j (a source node may have many such relay nodes in its neighborhood), then it will be the best relay for the source node i if the condition $argmin(d_{i,j} + d_{j,k}, N_j)$ holds provided the nodes are not dead. The Algorithm 3.1 shows selection of the best relay node for routing data towards the end destination. This Algorithm depicts the criteria of the best relay selection described above.

Fig. 3.2 considers all the possible cases in which the proposed protocol chooses a relay node. A source node A chooses either node B or C as the best relay. The term best relay (than better relay) is used in this situation because only two neighbors B and C are shown for the source node A. The sink is considered at the top for clarity. Actual data transmission from bottom to the surface sink may involve selection of more than one best relay nodes for a single data packet. The packet gets closer to the surface after forwarding by each intermediate best relay unless it reaches to sink (or is dropped if it does not find the best relay).

In Fig. 3.2, the circle having node A at its center indicates node A range of communication. Nodes B and C are shown in a similar fashion with circles around them. In case (a), nodes B

Algorithm 3.1 The Best Relay Selection

$BR \leftarrow$ the best relay
$d_{i,j} \leftarrow$ distance by which source node i is separated from relay node j
$d_{j,k} \leftarrow$ distance by which relay node j is separated from destination k
$R \leftarrow$ a node transmission range
$E \leftarrow$ energy assigned to a node
$N_i \leftarrow$ source node i neighbor set
$N_j \leftarrow$ neighbor set of relay node j
$M \leftarrow$ total deployed nodes in network
for $i = 1 : 1 : M$ **do**
  if $E_i > 0 \;\&\; E_j > 0 \;\&\; d_{i,j} < R$ **then**
    $BR = argmin(d_{i,j} + d_{j,k}, N_j)$
  else
sensor node is dead
  end if
end for

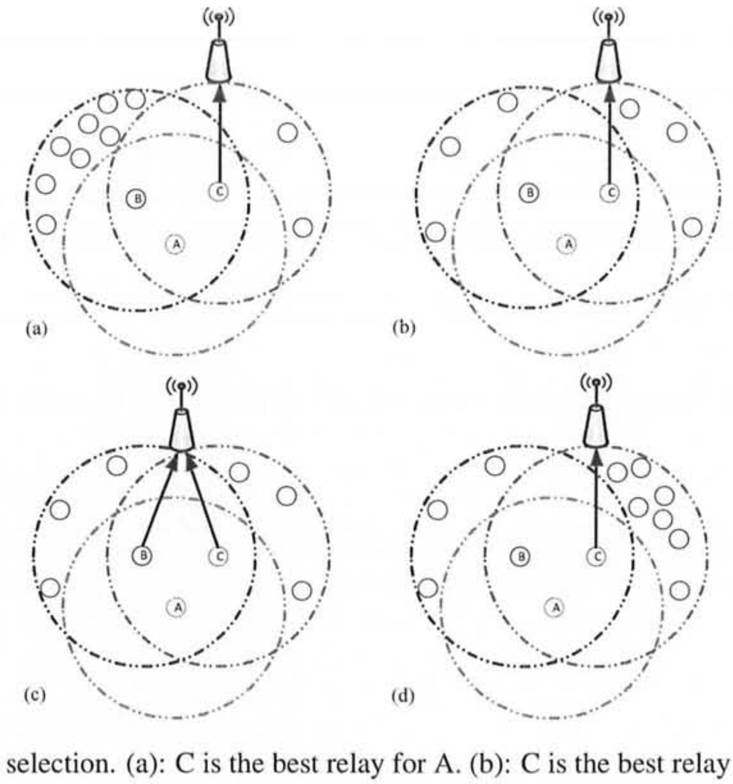

Figure 3.2 Relay selection. (a): C is the best relay for A. (b): C is the best relay for A. (c): Both B and C are the best relays for A. (d): C is the best relay for A.

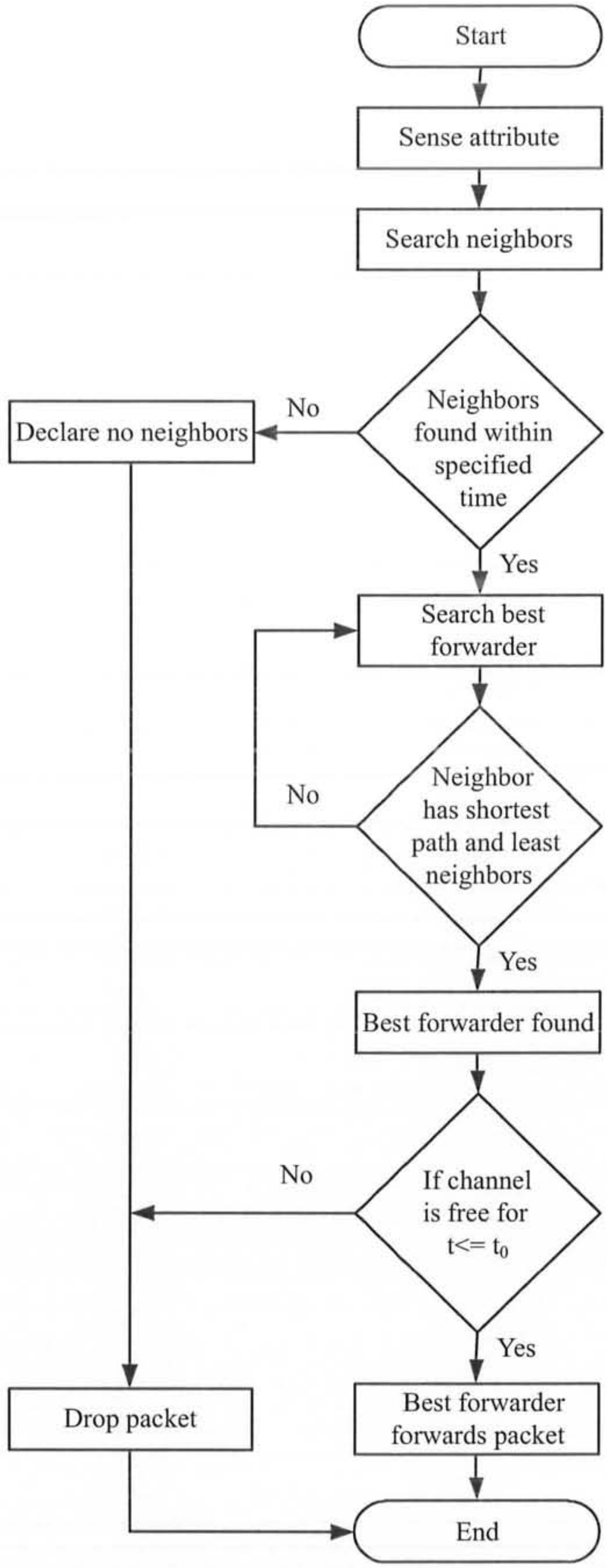

Figure 3.3 EEIRA flow chart.

and C make the neighbor set of A as they lie within its transmission range. Clearly, B has more neighbor nodes than C (B has ten neighbor nodes while C has four). In addition, C has shorter distance to the sink from A than B. Therefore, C is the best forwarder for A than B as it has the path of the least interference and the shortest distance. When A has to send data, it chooses C as a forwarder. For simplicity, only two neighbor nodes are shown for A (that is why we termed C as the best forwarder instead of better forwarder). Scenario (b) shows the case when B and C have the same neighbor set but the latter is closer to the sink. In this case, C is chosen as a forwarder of data by node A. The scenario when B and C both have the same neighbor set and are equidistant from the sink and A is depicted in case (c). In this case A may choose either B or C for data forwarding. Finally, case (d) indicates the situation when C has shorter distance from A to destination than B but has more number of neighbors than B. In this case, A chooses the shortest distance path and, therefore, forwards the data to C. Choosing B as forwarder in the last case forwards the packets away from the sink that is not desired. Therefore, node C is selected as a forwarder despite of its higher interference due to its greater number of neighbors than B.

3.4.4 Data Forwarding

Having neighbor's information, a node residing in the source region selects the best forwarder node among its neighbors in the relay region according to the above mentioned criterion. Packets get transferred to the best relay towards the destination. This process goes on unless packets reach the end destination. If there is no node in the neighborhood of a source node from relay region, it chooses another source node in the source region as a forwarder. This selected source node then chooses a relay node in the relay region (or another source node in the source region if it also does not find any neighbor in the mid zone) for data forwarding. A single node in the mid territory makes choice of a relay in the upper region. When no neighbor exists, it selects a relay node from the mid zone. This process continues unless packets are received by nodes in the destination territory, from where they are advanced to the in-range sink directly. Otherwise, advancement of packets is accomplished using a relay.

Fig. 3.3 depicts the flow chart that describes selection of the best relay in forwarding data packets by the proposed protocol. After network setup when nodes are deployed, exchange of hello packets is accomplished among nodes. A node waits for a specified time to hear from its neighbors. If it does not hear any neighbor within the specified time, it declares no neighbor at all. In this case, if a sensor node has data packets, it drops the packets. This dropping of packets continues unless the sensor node finds one or more neighbor nodes. However, when a node hears from its neighbors, it selects the best relay among its neighbors according to the above mentioned conditions. The best relay then transmits packets to the end destination. A node that is ready to initiate packets transmission senses the link to check whether it is free or not. If found free, packets transmission is accomplished towards the destination. If not free, it waits. The node drops the packets when it finds the channel busy until the expiry of the back off time to its maximum, t_0.

3.5 Simulations Results

The proposed algorithm is compared with counterpart schemes: multi criteria relay selection (MCRS) [74] and DBR [7]. The MCRS is applied in aquatic environment and chosen for comparison because it involves location, reputation (residual energy) and ratio of power of signal to noise to select a forwarder. The network deploys 100 sensor nodes in a random fashion. The transmission range of a single node is constant and spans to 200m in all directions and an initial energy of 70J. The LinkQuestUWM1000 modem is considered for data communication among nodes with a data rate of 10kbps [75]. A data packet is made of 50 bytes. The consumed power values are 10mW, 0.1W and 2W in idle, receive and transmit mode, respectively. The the MAC layer in [76] is considered. The random walk mobility model is considered to characterize the movements of nodes with water currents [7]. For the sake of fair comparison, only one sink localized at network top is involved in computation for all schemes (instead of multiple sinks placed at the top of the network in DBR). In the simulations, a single round corresponds to the time interval from the transmission of one packets by a single node to the successful reception at the end destination or drop during routing.

Fig. 3.4 depicts the way nodes die. The fastest rate with which nodes die is exhibited by DBR due to two reasons. Firstly, DBR selects the depth as a routing metric for packets routing that creates burden on low depth nodes near to water surface. Secondly, forwarders are selected within the fixed depth threshold. This leads to involvement of more forwarder nodes between any source-destination pair. As a result, nodes fully utilize their energy at the highest rate and are subjected to the fastest death. In MCRS, nodes with the highest location (network center), SNR and reputation values are preferred to take part in data forwarding. It reduces the number of forwarder nodes between a source-destination pair that, in turn, leads to less energy consumption and slower death of nodes than DBR. Selection of the shortest and the least interference path for routing data in EEIRA results in the involvement of the least number of forwarder nodes. In consequence, the rate with which nodes die is the slowest in this protocol than the competitor schemes. In essence, the shortest path and the least interference metrics in the proposed routing scheme result in the selection of the least umber of forwarder nodes in data routing. This, leads to the nodes death with a slowest rate

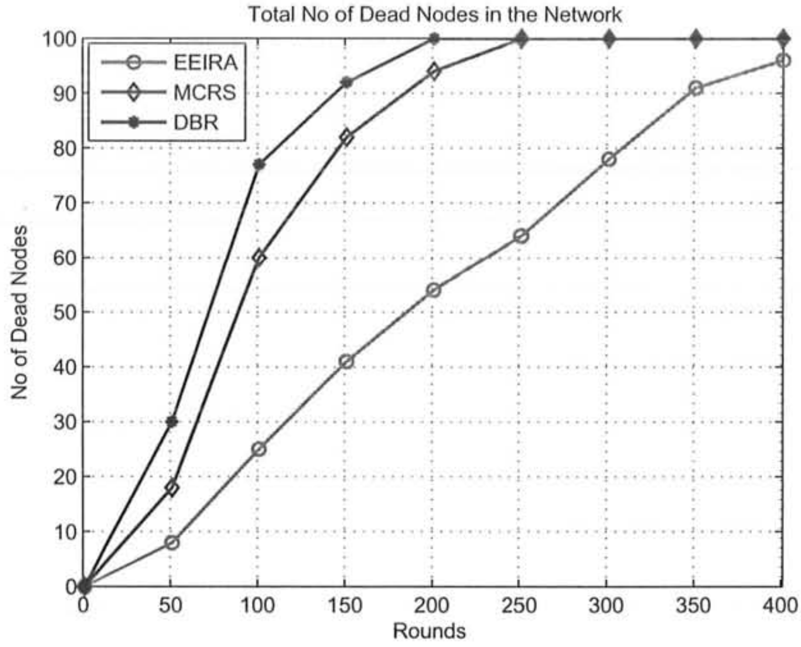

Figure 3.4 Dead sensor nodes.

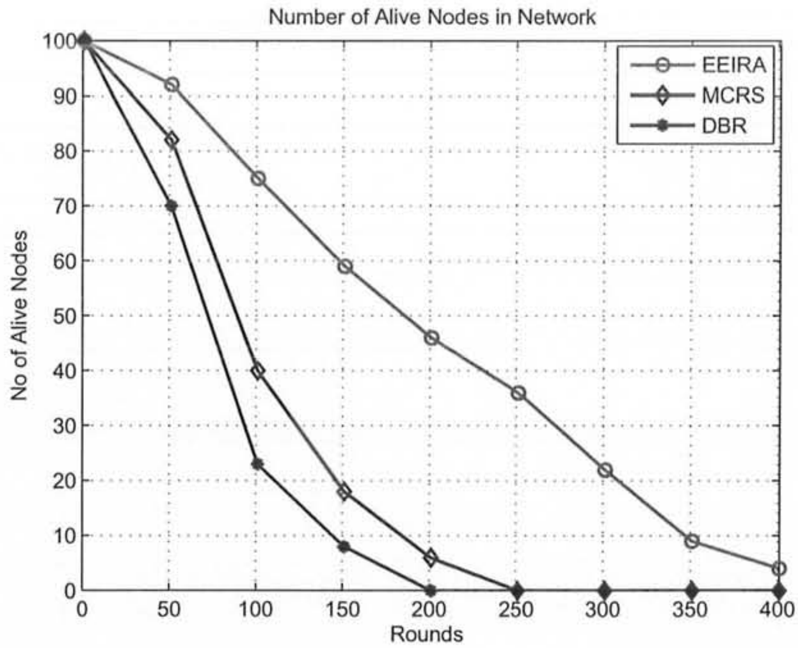

Figure 3.5 Alive sensor nodes.

as number of nodes involved in routing is the smallest. Fig. 3.5 depicts the behavior with which nodes remain alive. It is reciprocal of the corresponding behavior with which nodes die.

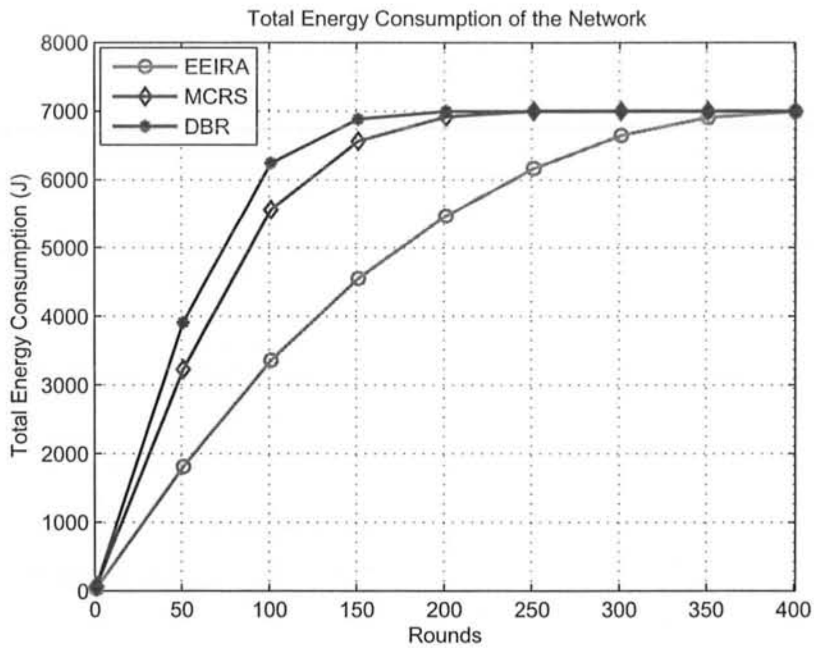

Figure 3.6 Energy expenditure.

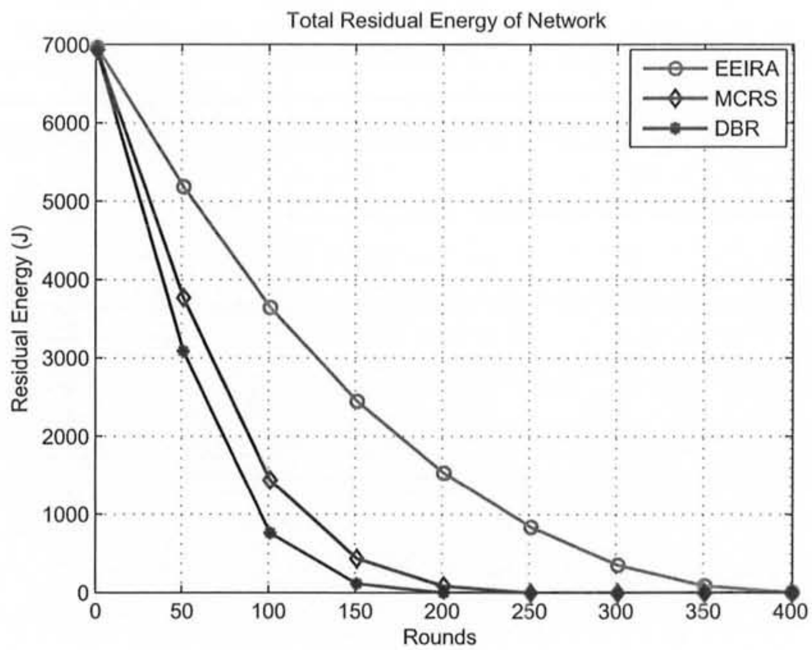

Figure 3.7 Residual energy.

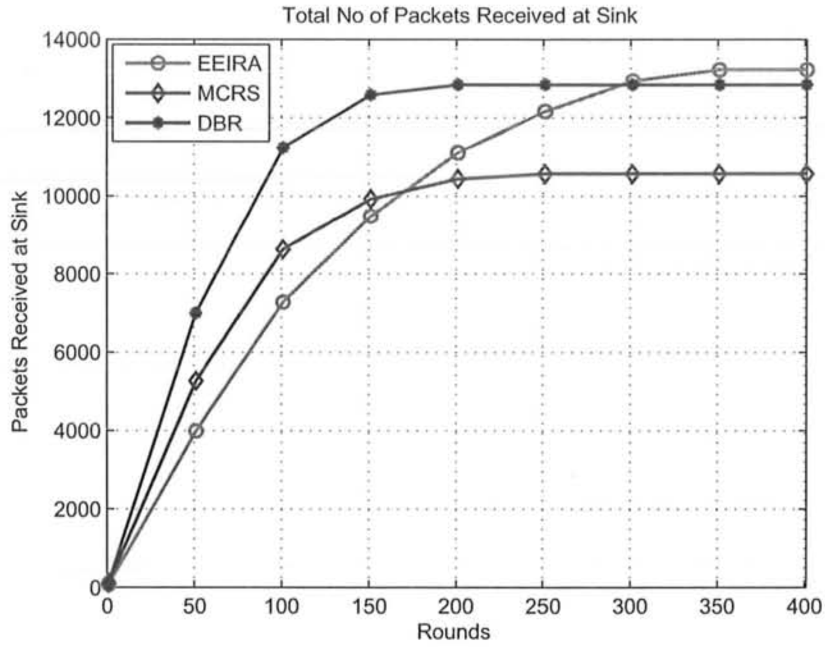

Figure 3.8 Total packets reception at end destination.

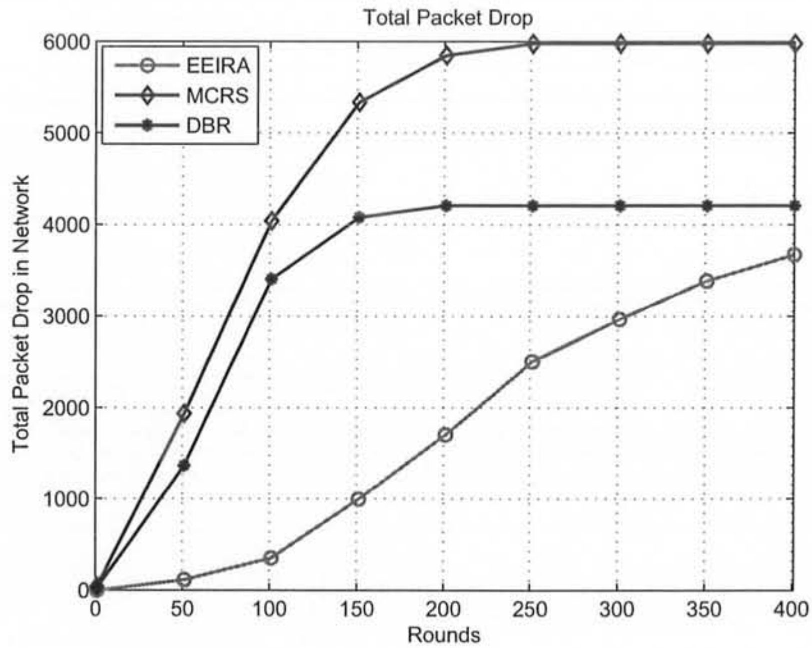

Figure 3.9 Total dropped packets.

The comparison of energy expenditure is depicted in Fig. 3.6. Nodes in EEIRA consume the smallest energy. The reason is that nodes die at the slowest rate in this routing technique that results in the least energy consumption. The relay selection criterion in EEIRA has the least number of forwarder nodes that leads to the least energy consumption. Energy consumption increases proportionately when more nodes contribute in routing. Initially up to several rounds, DBR and MCRS both have the same energy consumption as more forwarder nodes are available. As the number of rounds progresses, energy consumption increases noticeably in DBR due to selection of more forwarder nodes. In MCRS, forwarder nodes in the center of the network have greater location values and are preferred to be selected for routing the data along with the SNR and reputation values. In contrast, DBR chooses depth as the routing metric. So, it also considers nodes that are away from the center but have the same depth as the central nodes. Such nodes lie left and right (collinear) to the nodes in the center of the network. Sink, being on the top, causes involvement of more forwarder nodes in DBR than MCRS. Therefore, energy consumption is greater in the former than the latter.

The plot reciprocal to the total energy consumption is Fig. 3.7. Fig. 3.8 shows plot of the packets that reach to sink with success. For almost 295 rounds, the greatest number of packets reach the end destination for DBR due to the involvement of the low depth forwarder nodes and redundant packets forwarding. Following this, EEIRA has almost 22 % of alive nodes while there is no alive node at all in the counterpart schemes. The absence of alive nodes means no data sensing and forwarding. Therefore, packets reception at the end destination increases in EEIRA and becomes the highest at 300 and subsequent rounds. Both the counterpart schemes let more packets to proceed to sink than EEIRA for several rounds above the 100th round. It is due to redundant packets forwarding and selection of nodes close to the water surface in DBR. For MCRS, it is due to selection of the relay nodes in the mid of the network with high SNR values of the links. However, since nodes die at more rapid rates in these protocols, less forwarders are available in later rounds in these protocols. This decreases the throughput in the counterpart protocols. At the same time, the throughput of the proposed scheme increases as there are more alive nodes ready for data routing.

Fig. 3.9 depicts the total packets dropped during routing. The proposed scheme has the lowest packet drop as it chooses the shortest path with the lowest interference. Lowest interference path enhances the probability to transfer packets to end destination. This metric is not considered in the routing process in the counterpart protocols. As a result, packet drop is the lowest in EEIRA as compared to DBR and MCRS. The DBR drops less packets than MCRS because of the redundant packets transmission. The ratio showing delivery of packet is depicted in Fig. 3.10. The lowest packet drop and partially the highest throughput let EEIRA achieve the highest packet delivery ratio as compared to the competitor schemes.

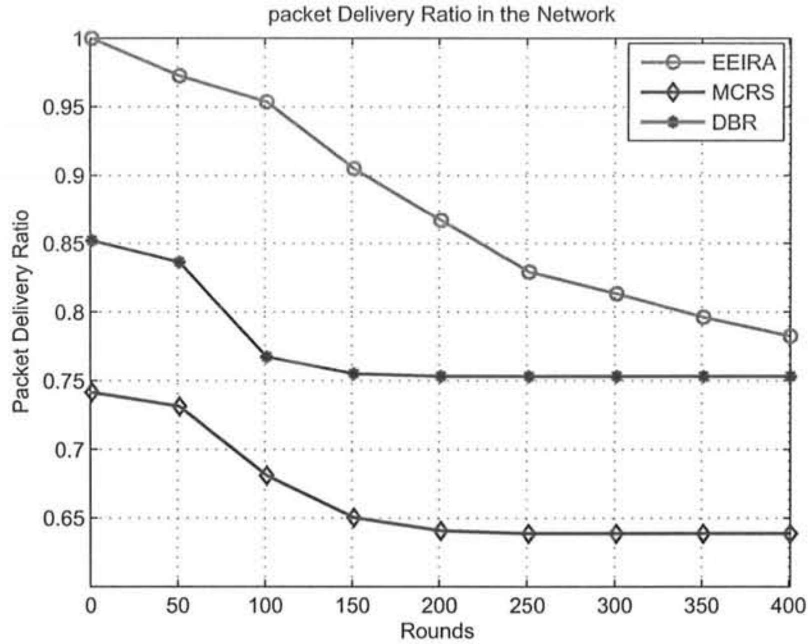

Figure 3.10 Delivery ratio of packet.

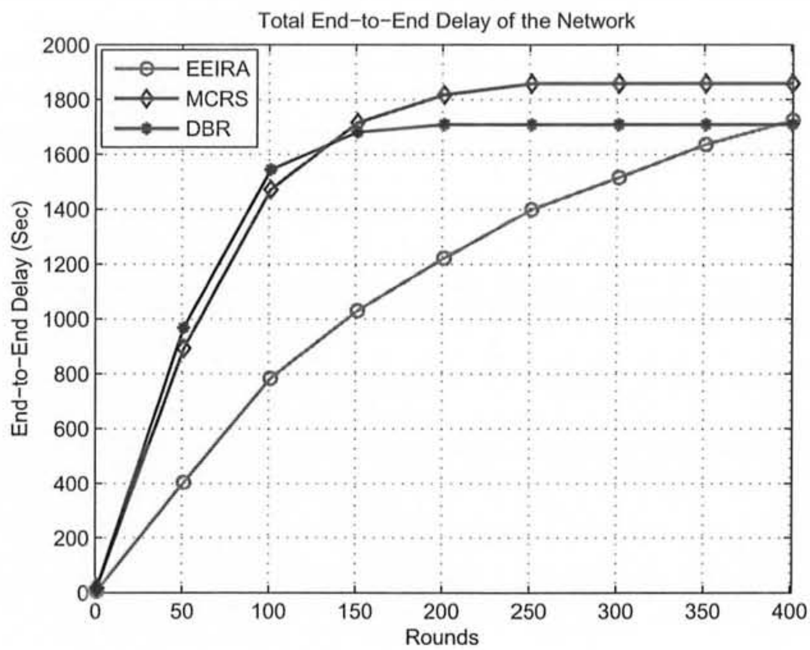

Figure 3.11 Network latency.

The DBR has better packet delivery ratio than MCRS due to its greater throughput and lower packet drop.

The plot of network latency is depicted in Fig. 3.11. The selection of the routing paths with the shortest distance (and lowest interference) from source to destination in EEIRA ensures the lowest latency as compared to DBR and MCRS. Initially, both DBR and MCRS have almost the same latency as the former utilizes low depth nodes and the latter considers nodes in the center of the network for data routing. As rounds progress, delay in DBR slightly increases due to the death of low depth nodes. After almost 130 rounds, delay increases in MCRS than DBR due to the death of nodes in the center of the network that are preferred for routing in MCRS. When nodes in the center die in MCRS, the bottom nodes are compelled to choose forwarders that are sidewise away from the nodes in the center. This leads to greater delay in MCRS than DBR.

This chapter proposes the EEIRA protocol to mitigate the interference during packets forwarding and reduce energy expenditure of the sensor nodes. Network partitioning is made into three sectors or regions. The bottom region is called source region as source nodes reside in it. The middle zone retains relay nodes. The top region below the water surface is called destination region and the corresponding nodes are termed as destination nodes. For data routing, source nodes select best relay nodes: nodes providing the shortest paths with the lowest count of neighbors. The shortest distance reduces the propagation latency. It also reduces the number of forwarders involved in the routing process that minimizes energy consumption. The selection of the lowest count of neighbors of the relay node reduces interference that, in consequence, reduces packet loss and efficiently utilizes the energy of the sensor nodes.

Chapter 4

EEIAR: Energy Efficient Interference Aware Routing for UWSN[1]

4.1 Introduction

Protocols related to interference avoidance in UWSN are the focus of attention in recent years. They provide optimal data traffic in accordance with the design parameters from bottom to surface of water. Analysis of such data then provides information and insight to the underwater environment under observation. Their design takes into account the challenges inherently associated with underwater communications: long propagation delay, low bandwidth and limited battery power [2]. These protocols are used in a number of applications as mentioned in [2][3][4].

Interference aware routing protocols are particularly important because of two reasons. Firstly, these protocols improve the quality of underwater communications. The received data packets at destination do not require rigorous treatment for extracting the desired information. This, in turn, reduces the complexity in the destination circuitry and shortens the response time for interpretation of the information. Such a response time is of significant importance in time sensitive applications such as detection of enemies' ships and disaster prevention. Secondly, they avoid high interference paths in transferring packets towards ultimate destination. This avoids packet drop and collision and, consequently, increases the probability that packets reach the end destination with success. Packet drop due to interference is one of the major challenges keeping in view the finite battery power of nodes.

[1]The basic idea of the journal paper: Anwar Khan, Nadeem Javaid, Ihsan Ali, Mohammad Hossein Anisi, Atiq Ur Rahman, Naeem Bhatti, Muhammad Zia, and Hasan Mahmood, "An energy efficient interference-aware routing protocol for underwater WSNs," *KSII Transactions on Internet and Information Systems*, Vol. 11, No. 10, pp. 4844-4864, October 2017, bases on the contents of this chapter.

It also leads to loss of information and critical data that are always undesired. Long and persistent operation of nodes demands that their limited energy is utilized in an efficient fashion.

The conventional depth based routing protocol [7] and other routing techniques [10][17] [18][19] route the packets from source to destination using the flooding approach. However, it leads to redundant packets transmission, interference and packet collision. This causes unnecessary energy consumption to a significant extent. Also, with depth as the routing metric, the low depth nodes overburden due to frequent selection as forwarders and die soon leading to holes formation. Creation of holes losses packets and reduces the probability of finding a forwarder node. Energy efficient depth based routing (EEDBR) protocol [47]; although reduces energy consumption in DBR, it also rapidly utilizes high energy nodes that are near the water surface. The death of such nodes increases packet loss. Although DBR makes use of packet history buffer and packet holding time to avoid redundant packets transmission and interference, forwarding packets in a flooding manner does not appreciably overcome these issues as every node receives packets from all nodes within its transmission range or within the depth threshold. A receiving node of a packet routes it to the sink if it comes from a higher depth node. This forwarding of packets in a greedy manner causes a single packet transmission unnecessarily by more than one node. It is because due to long delay in underwater communications, nodes with comparable holding time difference forward the same packets before they overhear one another (overhearing controls same packet transmission by many nodes).

The design of interference aware routing protocols carries a number of challenges. The underwater medium is highly time varying and fluctuating [77] due to which the packets transmitted towards destination are severely affected by its properties. This may include scattering of the signal of interest by the molecules of water and underwater objects, severe noise, interference and shadow zones. Also, redundant packets transmission to successfully send the packets from source to destination; even if some packets drop along the routing path, causes additional interference and packet collision. If such redundant packets are not properly cope with, the result is packet collision, interference and finally packet loss. The proposed work addresses some of these challenges.

This chapter proposes the EEIAR routing protocol for UWSN. It avoids interference while advancing packets from source to destination. To forward data, forwarder nodes that have the least number of neighbors and the lowest depth are selected as the best forwarders. Choosing such forwarder nodes avoids interference in transmission and reception of packets. The lowest depth brings packets near to surface every time they are forwarded. Unlike forwarding the packets in a flooding fashion, a sender node decides and selects the best forwarder node.

Such a decision reduces energy consumption by controlling packet collision and interference due to redundant packets transmission. The choice of selection of a forwarder node by a sender node further allows it to select forwarder nodes within its full transmission range. This is contrary to most of the flooding based routing protocols that usually select forwarder nodes within the fixed regions to reduce energy consumption and redundant packets transmission [7][10]. As a result, the probability of unavailability of a forwarder node reduces. This, in consequence, increases the successful packets reception probability at the sink. The protocol is unique from the existing protocols in a number of ways. Firstly, it relaxes the condition for the requirement of localization of nodes which by itself is challenging. Secondly, a sender node selects relays using its complete communication range without a threshold as considered in DBR and EEDBR. This reduces propagation latency and energy expenditure by controlling intermediate relay nodes in transferring packets towards end destination. Thirdly, a single sink is positioned at tope middle surface unlike the DBR and EEDBR protocols that deploy multiple sinks. This strategy evaluates the effectiveness of selection of the lowest depth nodes during data forwarding when multiple sinks are not present. Fourthly, the partition of the network into source, relay and destination regions makes forwarder selection a convenient task. Moreover, unlike the conventional approach in UWSN that anchors few nodes at sea bed, the proposed approach considers that every node in the network is capable of sensing the attribute of interest and forwarding other nodes's data. This provides greater coverage area and flexibility in data sensing and transmission over the conventional approach.

4.2 Related Work

The authors in [78] propose interference aware routing and scheduling policies for sensor nodes to achieve energy efficiency and efficiently utilize the available bandwidth in underwater communications. The scheduling policies give priority to nodes that are capable of earlier transmission of packets than others, have greater number of packets in their buffers, are positioned farther from the sink and have sent less number of packets. These policies result in minimized time difference between the readiness of a packet for transmission and its effective transmission time. They also result in reduction of the path from source to destination, buffer size of forwarder nodes and data traffic. In addition, packets are transmitted with varied set of power levels. Various combinations of these scheduling and routing policies are combined to obtain the optimal result. However, the proposed system is based on too many assumptions in the routing and scheduling policies that make it less practical to implement. The work in [13] designs a routing protocol that avoids interference and holes formation for reliable data transfer. A node ready to initiate transmission selects a potential forwarder node among its neighbors. It first calculates a cost function based on the presence of the count of the nodes in vicinity of the forwarder, its distance from the sender and hop count from sink. Packets are then forwarded to the potential forwarder node that has the highest cost function. However, the calculation of cost function involves too much computation parameters. In addition, the protocol overburdens the nodes close to water surface. These nodes die soon that results in formation of energy holes. The authors in [79] propose three protocols. In the first protocol, a sender node selects a forwarder node within its transmission range that has smallest depth and highest battery power level. However, such nodes die early that creates holes in the network. Formation of holes results in degraded system performance. The second protocol makes use of the present power content of the battery, neighbors nodes and the residual energy of the expected relay. However, high energy nodes still die as the routing process continues. The third protocol involves the use of the least residual energy, lowest depth within the depth threshold and the presence of neighbors nodes in the vicinity of the expected relay. Again, holes are created when low energy nodes die.

The algorithm presented in [80] propose an improved interference aware EEDBR (iIA-EEDBR) protocol to avoid the creation of holes, prolong network lifetime and enhance throughput. Half of the nodes are deployed in sensing mode and the rest in the sleeping mode. The network is segmented into four logical sections based on depth. Every section has a header node with which the sleeping nodes exchange their depth, ID and section number information. When a sensing node in a section dies, the header node turns a sleeping node into a sensing node. The protocol works in two stages. In the first stage, nodes exchange information of depth and the energy left in the battery. During the second data transmission stage, sender nodes forward data packets to neighbor nodes that have the highest residual energy, the least number of neighbors and the lowest depth. However, the performance of this protocol severely degrades when the header node dies due to constant monitoring of sensing and sleeping nodes and taking part in the routing process. In addition, a node may die in one location and a sleeping node may become active in a different location. Therefore, it my not effectively counteract the effect of the death of a sensing node. The work in [81] proposes energy balanced interference aware EEDBR (EB-IAEEDBR) that balances energy consumption in IEEEDBR protocol. Initially, nodes have same energy. As the protocol operates, the energy grade of nodes changes. When a node is ready to initiate transmission, it looks at the energy grade of next expected forwarder. If a receiving node has greater or equal energy grade to a sender node, the former receives the packet from the latter. Under the condition of a node having energy grade below a threshold, it transmits a control packet to one-hop neighbors. The neighbors know it and start direct transmission to the sink. In this way, the protocol achieves energy balancing by not choosing forwarder nodes that have energy below a certain threshold. The protocol switches from the initially multi-hop communications to direct transmissions when high energy nodes start to die (as is the case with EEDBR). The research in [82] proposes a channel aware routing protocol that considers the speed of sound and the channel noise with respect to depth to route packets towards end destination. The protocol functions in two modes. The collecting mode (CM) in which nodes share neighbor information and the direct mode (DM) in which a sender node forwards data to a forwarder node. A source node first constructs an ideal virtual path to the sink and then calculates a weighting function for every forwarder node based on the probability of successful transmission and distance calculation among ideal path, expected relay and ultimate destination. A relay with the highest weighting function is then selected for data forwarding. The protocol outperforms the counterpart scheme in transferring more packets to the ultimate destination with shorter latency. However, the protocol involves localization information of nodes that constraints its application. The authors in [83] propose two protocols: energy hole repairing DBR (EHRDBR) and interference-bandwidth aware DBR (IBDBR). The former chooses relays based on interference, battery power level and depth while the latter chooses them by considering interference, bandwidth, residual energy and depth. In both protocols, when a node dies, a live node moves to its location to avoid hole creation. These protocols show promising behavior in transferring packets to the end destination, lowering propagation latency and network life span. However, locating the position of a dead node and replacing it with a live node requires localization information, which is troublesome to do, especially when nodes are not stationary and move with water currents. In addition, considering too many parameters for forwarders selection increases the computation time that introduces delay in forwarder selection process.

4.3 Channel Model

The channel model involves the equations of channel noise, acoustic speed, transmission and spreading losses in the same manner as described in Chapter 3.

4.4 Proposed Protocol

4.4.1 Network Architecture

The proposed network is a cube having 500m length of a single face as depicted in Fig. 4.1. Within this cube, sensors nodes follow random deployment pattern. The sink position is on the middle of the network on water surface. In order to distinguish among source, relay and destination nodes, the network total depth D is segmented into three sectors or regions. The topmost sector has depth in the range defined by $0m < D \leq 167m$ and is called

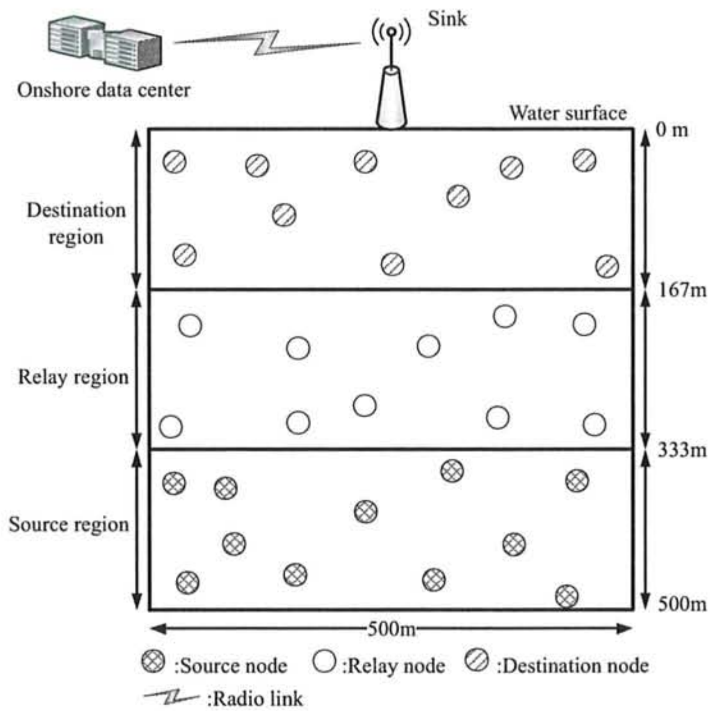

Figure 4.1 Network architecture.

destination region as it lies close to the sink (destination). Nodes in this sector are called destination nodes. The mid sector has depth specified by $167m < D \leq 333m$ and is called relay or forwarder region. The terms relay and forwarder are used interchangeably unless stated otherwise. Nodes in the bottom source sector are called source nodes with their depth defined by the range $333m < D \leq 500m$. The bottom source nodes forward data to the mid relay nodes that further forward it to the destination nodes. From the destination region, data is sent to the surface sink. Nodes make use of acoustic links to mutually communicate as water badly attenuates radio waves. The sink, on the other hand, communicates with data center terrestrially located near water surface using a radio link and with sensor nodes through acoustic links. Packets reception at sink is considered as transferred to the data center near water surface as radio waves are involved.

4.4.2 Neighbor Identification

After deployment of nodes, initially they do not know about the depth and neighbors information of one another. Every node broadcasts a hello signal, which is received by its neighbor nodes. The message contains the depth information and ID of the broadcasting node.

Every neighbor node replies to the hello message of the broadcasting node that processes the received messages and gains information about its neighbors. Every node then constructs a table of its neighbors and broadcasts it. In this fashion, every node becomes aware of its own neighbors and the neighbors of its neighbors along with their depth information. The knowledge of depth and number of neighbors helps a sender node to select the best forwarder node among its neighbors (based on these information) in sending data towards destination. The broadcasting node waits for a reply from every neighbor node in response to the hello message for a certain time proportional to the propagation and processing delays in underwater communications. If it does not receive any reply from any node, it sends the hello message again. It declares no neighbor at all when the hello message is sent for the maximum number of times and gets no response within the specified maximum waiting time.

All nodes periodically exchange the hello messages and the neighbor tables to remain updated about the alive number of neighbors as nodes die due to consumption of their limited battery power. In addition, existing neighbors of a node may leave or new may come within its transmission range with water currents. When a sensor node becomes dead, it can not reply to the hello messages of its alive neighbors. The alive neighbors, therefore, exclude the ID of the dead node from their routing tables. In essence, this results in the recognition of the dead nodes.

4.4.3 Data Forwarding

When a source node in the source region senses some attribute, it is converted into packets of information or data. A forwarder node is then chosen by the source in the mid forwarder region within its transmission range to send packets to it. The source node chooses only that forwarder node that satisfies the criterion of being the best relay: node having lowest depth and the lowest count of neighbors. If a source node is missing neighbors inside the forwarder region, it opts to choose forwarders in the source region. Such a forwarder source node then chooses another forwarder node in the forwarder region for packet forwarding that further sends the packet to destination nodes. If there are no neighbors at all, the packet is dropped. Packets are transferred to the sink by destination nodes. When a source node in the source region has both source nodes in the source region and forwarder nodes in the forwarder region within its transmission range, it selects the forwarder node from the forwarder region automatically because of its lower depth than the source nodes in the source region. Nodes that lie in the mid region and the top destination region use the same routing strategy to forward packets towards the sink. It is assumed that all nodes are worthy of sensing the desired attribute. Every sender node sends packets to a forwarder only when it finds the channel to be free, else it waits. The packet is dropped when the process reaches to its maximum limit.

Selection of the lowest depth nodes ensures that a data packet becomes closer to the sink after every time it is forwarded by a forwarder node. The choice of a forwarder node having lowest neighbors reduces the interference. This also minimizes packet collision and, in turn, minimizes packet drop. It contributes to energy efficiency too as the least possible forwarders participate in routing. The decision of routing packets by a sender node (rather than by a node receiving it) further reduces redundancy in packets transferring to the end destination. This approach is unlike the behavior of the flooding protocols as referred in related work section that causes excessive energy consumption. A node that has to send data chooses another forwarder in its neighborhood based on the same defined criterion when a previous forwarder dies. The death of a sensor node is automatically detected when it does not respond to the periodic hello messages. The ID of a dead node is excluded from the neighboring table that nodes broadcast to identify neighbors.

Upon receiving a packet, a forwarder holds it for a particular interval of time termed as the holding time. It depends upon the depth, number of neighbors and the time interval in which the forwarder nodes successively receive two packets. However, every received packet is never kept for more than the system characteristic maximum holding time. A timer records the reception time of every packet. If channel is found busy and the maximum holding time expires, the packet is declared as dropped.

The Algorithm 4.1 shows the way the best forwarder selection is accomplished. The node i has to choose a best forwarder within its vicinity from its neighbor set N_i. A neighbor node j with the lowest depth and the lowest nodes in its neighbor set is selected as the best forwarder. This procedure repeats until the packet reaches to sink or is dropped.

Fig. 4.2 shows all the possible cases that a sender node may encounter in forwarding data packets. The dotted circles are indicative of the communication range of nodes A, B and C that lie in their respective centers. In all cases, node A is the sender of data packets while node B or C is the expected forwarder. For simplicity, only two nodes are shown as neighbors of A. In scenario (a), C has lower depth and less number of neighbors than B. Therefore, A chooses C for data forwarding. In case (b), C has lower depth than B but more number of neighbors. The more number of neighbors of C than B associates more interference along the path involving C. However, A still chooses C because choosing B forwards the packets away from the sink. In situation depicted in (c), both B and C tie in having equal neighbors and depth. Therefore, A may choose either B or C for data routing. Finally, in (d), B and C have the same depth but C is chosen to route data due to its less number of neighbors (and less interference).

Algorithm 4.1 The Best Forwarder Selection

$BF \leftarrow$ The best forwarder
$E_i \leftarrow$ Energy of the sender node i
$N_i \leftarrow$ Nodes in neighborhood of the sender node i
$D_i \leftarrow$ Depth of the sender node i
$E_j \leftarrow$ Energy of the expected forwarder j
$N_j \leftarrow$ Nodes in the neighborhood the expected forwarder j
$D_j \leftarrow$ Depth of the expected forwarder j
$M \leftarrow$ Total nodes within the network
for $i = 1:1:M$ **do**
  if $E_i > 0$ & $E_j > 0$ & $j \in N_i$ **then**
    $BF_i = argmin_{j \in N_i}(D_j, N_j)$
  else
Nodes are dead or have no neighbors
  end if
end for

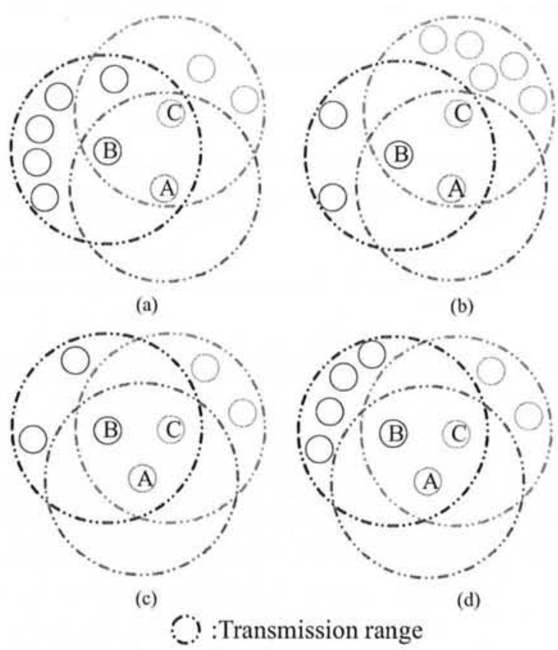

Figure 4.2 Forwarder selection. (a): A chooses C. (b): A chooses C. (c): A chooses either B or C. (d): A chooses C.

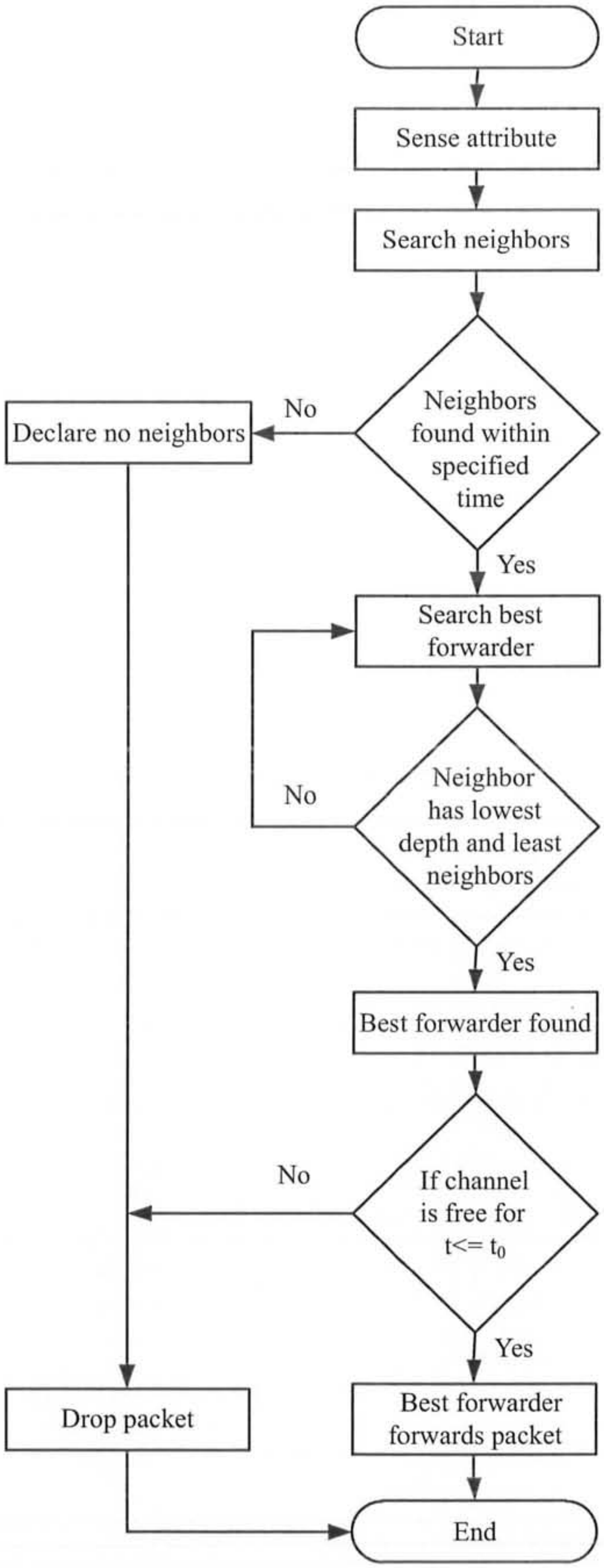

Figure 4.3 EEIAR flow chart.

Fig. 4.3 depicts the flow chart that elaborates the operation of the routing protocol. After sensing an attribute, a sensor node searches for its neighbors using a hello message described above. The neighbor searching is accomplished in a continuous fashion. Upon finding neighbors, the best forwarder is selected according to the criterion as described above. A sensor node declares no neighbor at all when it does not receive any reply from any node within the specified maximum waiting time. In such a condition, packets are dropped. This dropping of packets continues unless one or more neighbor nodes are found.

4.5 Simulations Results

This section gives a description of the simulation results and compares the proposed scheme with DBR and EEDBR as they also take into account depth as the routing metric (EEDBR takes into account the residual energy too in deciding forwarder). This is the primary reason due to which the proposed protocol is compared with these protocols. Both, DBR and EEDBR, place multiple sink nodes at the upper surface of water. The proposed protocol, on the other hand, considers only one sink at the surface of water. This may not effectively exhibit the performance comparison of these protocols as the availability of multiple sinks at the water surface affects the performance parameters. Therefore, in accomplishing fair comparison, a single sink is mounted on the middle on the network at water surface in all the three protocols (EEIAR, DBR, EEDBR). This approach is unlike the usual approach where DBR and EEDBR are implemented with multiple sinks at the water surface. It also shows how the performance of DBR and EEDBR will be affected when multiple surface sinks in these protocols are reduced to only one. Moreover, the DBR and EEDBR consider two sensing nodes at the bottom of the network. This condition is relaxed in the proposed simulation setting that assumes that every node can detect the attribute under consideration. This provides greater flexibility to the network sensing and coverage area, as usually required by the real world applications.

The network is an underwater cube of dimensions $500m \times 500m \times 500m$ with 225 nodes randomly deployed in it. The mobility of nodes is modeled by the random walk pattern as considered in the DBR protocol. Every node uses the LinkQuest UWM1000 acoustic modem for communicating with other nodes. The MAC layer is addressed as given in [76]. The transmission range is kept fixed at 100m for every single node. Every single node consumes 2W, 0.1W and 10mW power in transmitting, receiving and in idle state, respectively. A sensor node generates one data packet in one second. A single packet sizes to 50 bytes with 10kbps data rate.

Fig. 4.4 depicts the energy expenditure. On account of choosing the best relays for data routing, the proposed scheme has the least interference and packet collision. Also, since a sender decides a forwarder, redundant packets transmission is minimized. These phenomena contribute to unnecessary consumption of energy that the proposed protocol avoids. In addition, choosing a forwarder node with the least number of neighbors avoids looping a single packet back and forth between neighbors of the forwarder node itself. It is because with few neighbors, the probability that any two neighbors have the same depth and number of neighbors reduces. If such nodes lie within the transmission range of each other, they may be the forwarder nodes of each other and will send the same packet to one another multiple times. This, in turn, minimizes nodes that participate in data routing. Selection of the shortest path in the proposed scheme further reduces the number of forwarders participating in routing. Consequently, the EEIAR has the least energy consumption. In contrast, DBR selects only the lowest depth nodes for data forwarding. Every node receiving a packet in DBR forwards it to the sink if it comes from a higher depth node. This causes excessive energy consumption in DBR that makes its energy utilization the highest. The EEDBR has lower energy consumption than DBR due to the selection of less forwarder nodes and suppression of the redundant packets transmission than DBR. Fig. 4.5 exhibits residual energy behavior. Its pattern is reciprocal to the behavior of the expenditure of energy.

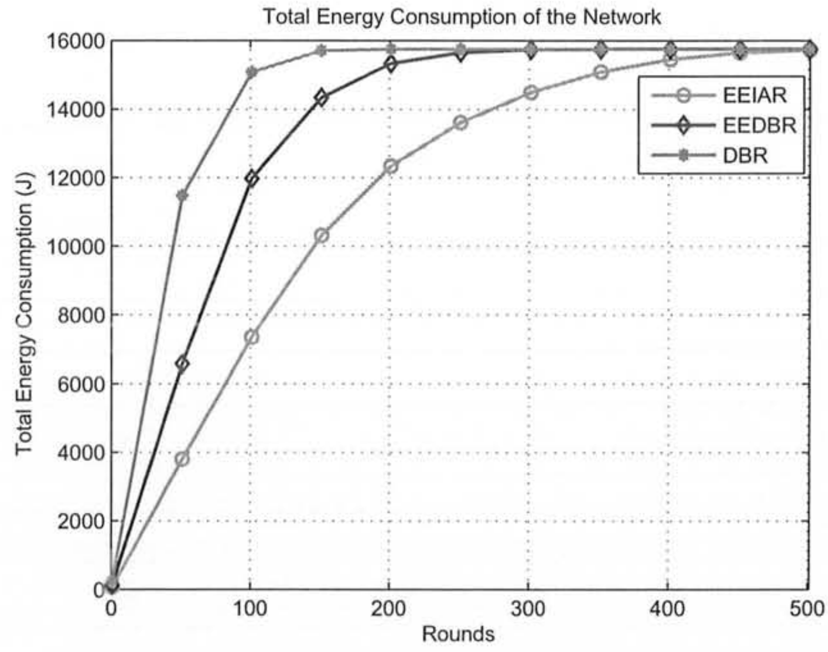

Figure 4.4 Energy expenditure.

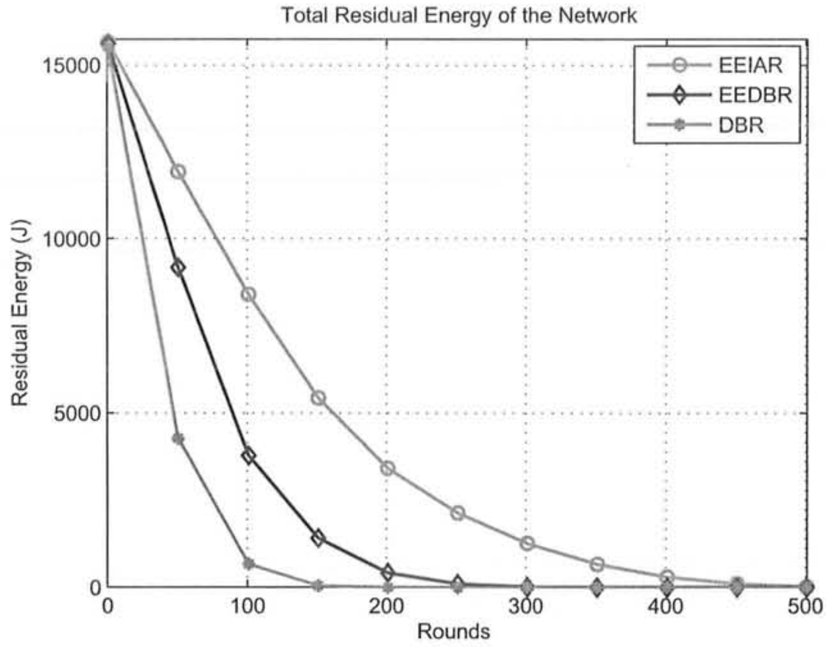

Figure 4.5 Alive nodes.

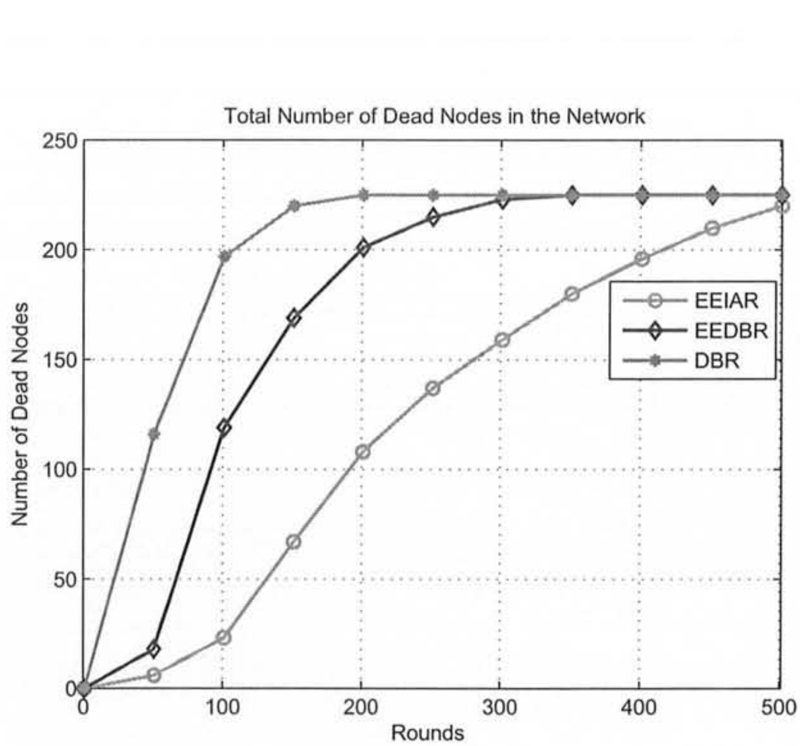

Figure 4.6 Dead nodes.

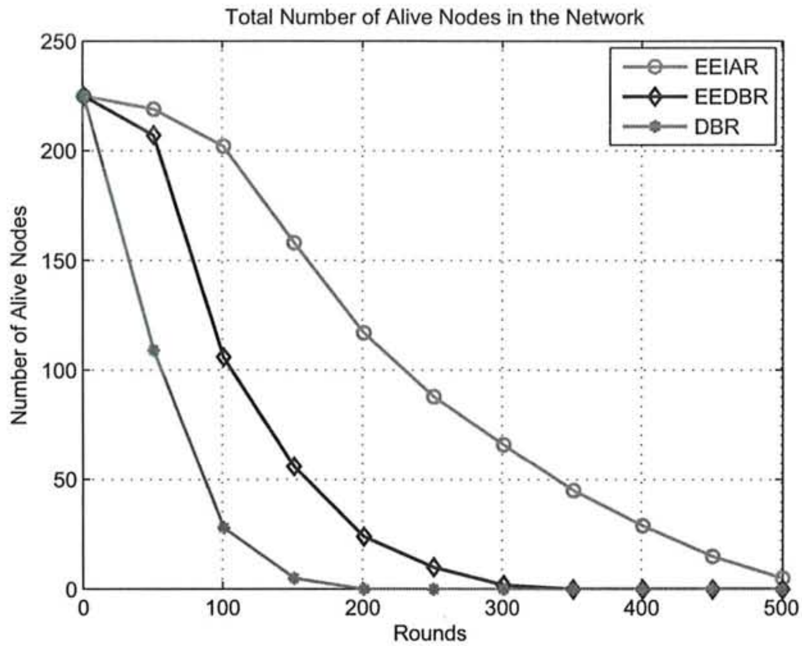

Figure 4.7 Residual energy.

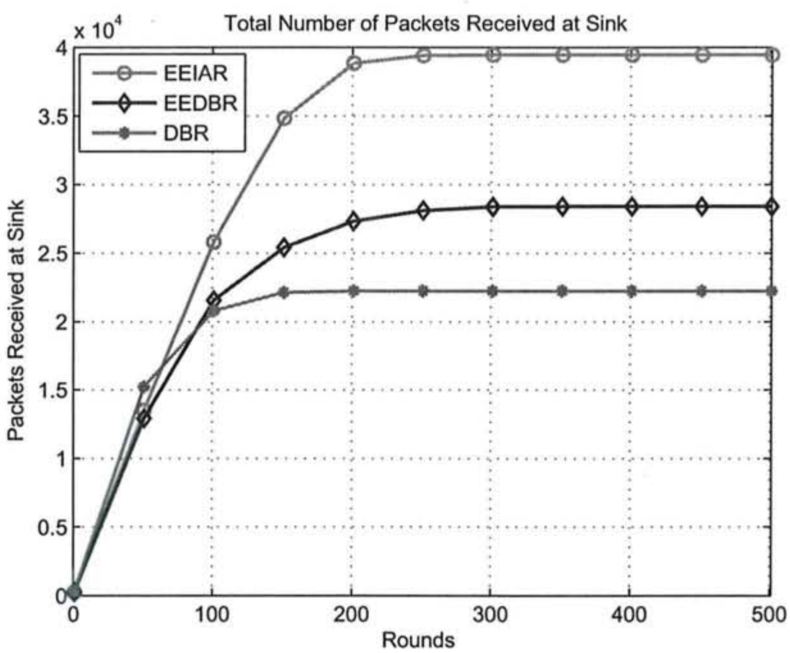

Figure 4.8 Packets transferred to sink.

The patterns followed by the protocols in depicting the ways in which nodes die is shown in Fig. 4.6. On account of the lowest energy expenditure, nodes death rate is slowest in EEIAR. The greater energy consumption in DBR subjects its nodes to die at a corresponding rate. Fig. 4.7 depicts the patterns in which nodes remain alive. This pattern exhibits a reciprocal relation to dead nodes.

Fig. 4.8 depicts nodes that reach to sink with success. Initially, for almost the first 50 rounds, packets reception at the sink is slightly the greatest for DBR. It is because DBR chooses the lowest depth nodes that are closest to the surface of water for packets forwarding. As rounds progress, these nodes overburden and die rapidly. Death of such nodes reduces the availability of forwarder nodes to receive and forward packets to the sink. Consequently, its throughput decreases and becomes the lowest after 100 rounds. The slowest death of nodes and selection of the path of the least interference for data routing in EEIAR ensure the availability of forwarder nodes and its throughput becomes the greatest after 57 rounds. The less rapid death of nodes in EEDBR makes its throughput greater than DBR after 100 rounds when most of the lowest depth nodes die in DBR. The comparison of total packet drop is

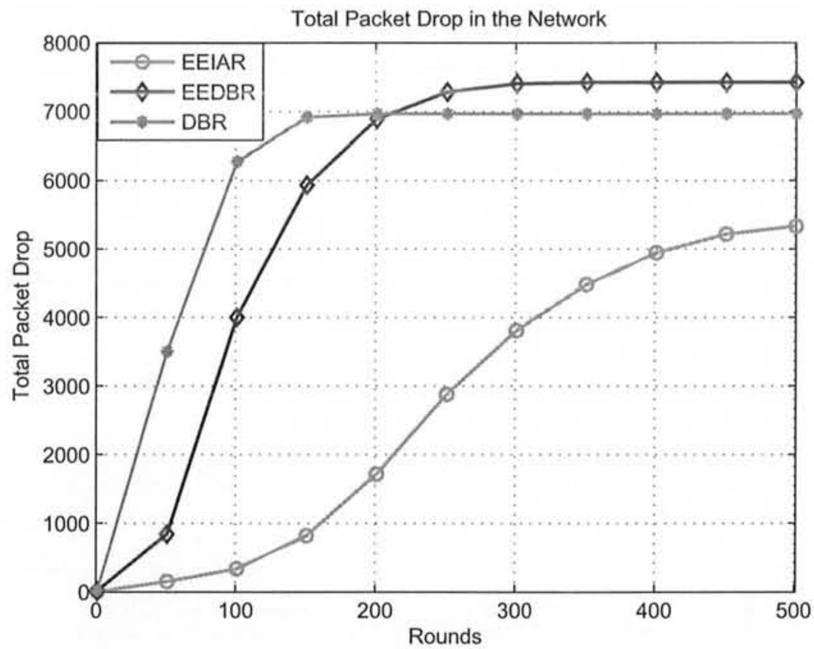

Figure 4.9 Dropped packets.

shown in Fig. 4.9. By virtue of the slowest rate of nodes death and adapting the path of the least interference in packets forwarding, EEIAR exhibits the smallest number of dropped packets. For the first 207 rounds, as compared to EEDBR, DBR has greater packet drop by virtue of having more rapid rate of nodes' death. Beyond this, all nodes are dead in DBR that

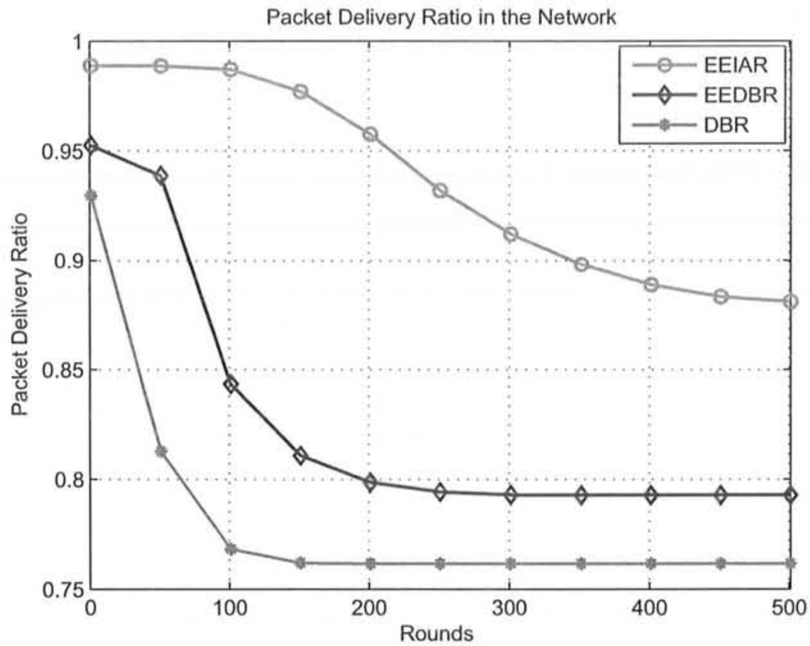

Figure 4.10 Delivery ratio of packet.

makes its packet drop constant while the corresponding packet drop in EEDBR increases as several nodes are still alive. Fig. 4.10 shows the ratio of packet delivery. This parameter is highest for the proposed scheme. The reason for this involves the corresponding drop in packets and delivery of packets to sink. Finally, Fig. 4.11 depicts the network latency. This parameter is the smallest for the proposed scheme for the first 100 rounds, as it involves the least forwarders. After that, its delay becomes greater than DBR because more nodes are alive in the proposed scheme that takes part in data routing compared to DBR in which most of the nodes are dead. After 200 rounds, delay becomes greater in EEIAR than EEDBR by virtue of more alive nodes in the former that route the packets unless they all die at almost 500 rounds. For the first 50 rounds, DBR and EEDBR have the same latency by virtue of the availability of more forwarder nodes in both schemes. As number of rounds increases, nodes die faster in DBR than EEDBR so less number of nodes remains alive in the former to forward packets. As a result, delay becomes greater in the latter due to more alive nodes available for routing.

This chapter proposes the EEIAR protocol for UWSN. The segmentation of the network is accomplished into source, relay and destination regions, based on depth. In forwarding data packets from bottom to top of the network, the best relay (or forwarder) nodes are selected. A node having the smallest depth and lowest count of neighbor is chosen as the

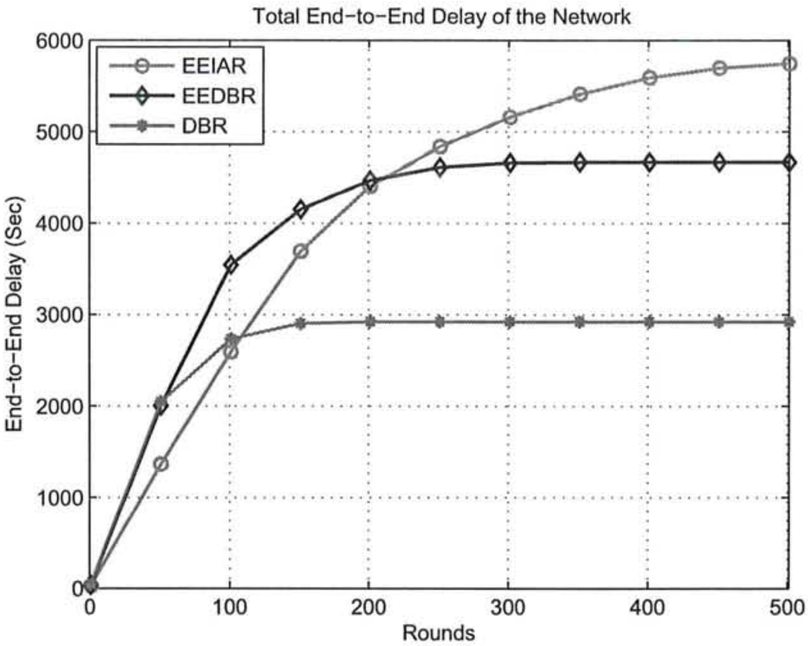

Figure 4.11 Network latency.

best relay node. Such a choice results in reduced energy expenditure. It also reduces packet drop that increases the packet delivery ratio.

Chapter 5

LF-IEHM: Localization-Free Interference and Energy Holes Minimization Routing for UWSN[1]

5.1 Introduction

Overcoming interference and energy holes in UWSN usually guarantees reliable data transfer from source to destination. However, addressing these issues is linked with addressing the inherent challenges of underwater communications: low available bandwidth, greater propagation delay than terrestrial RF communications and limited battery power [2]. These networks find several applications as mentioned in [2][3][4].

Underwater routing protocols that involve mitigation of interference and energy holes are unique because of a number of reasons. Interference results in packet collision that, in consequence, leads to packet loss. In a similar fashion, formation of energy holes disconnects the routing traffic from source to destination that also results in data loss. Such losses are unbearable in underwater communications where sensor nodes already operate on limited battery power. Therefore, protocols coping with these issues provide reliable transfer of packets to the end destination. Such data delivery is particularly important in time sensitive and military applications [77]. Specifically, when data loss due to interference is overcome, the limited battery power of nodes is also utilized in an effective and efficient fashion. The power that is lost against interference is now utilized to deliver more data packets. Likewise,

[1]The basic idea of the journal paper: Anwar Khan, Ismail Ahmedy, Mohammad Hossein Anisi, Nadeem Javaid, Ihsan Ali, Nawsher Khan, Mohammed Alsaqer, and Hasan Mahmood, "A localization-free interference and energy holes minimization routing for underwater wireless sensor networks," *MDPI Sensors*, 18(1): 165, pp. 1-17, January 2018, bases on the contents of this chapter.

when an only forwarder node between a sender and a receiver dies and becomes an energy hole, it leads to loss of data from sender to receiver. The data loss causes unnecessary power consumption of the sender node. Therefore, overcoming this energy hole ensures reliable data delivery as well as efficient power utilization.

The conventional routing protocols that cope with the energy holes require that the localization information of an energy hole is known [42][84]. However, localization is cumbersome and challenging as it usually requires extra computation and also leads to inaccuracy in the measurement of position of an energy hole. Furthermore, an energy hole may change its position and nodes may not detect it early due to long delay in underwater communications. As a result, false positions detection of all the energy holes may compromise the performance of the network. The protocols addressing the interference select routing paths that involve the least number of neighbors of a forwarder node [57][78]. However, with the least number of neighbors, a forwarder may not forward packets further when its neighbors die. In other words, death of the least number of neighbors of a forwarder node results in formation of energy holes. This also results in overall degradation of network performance. This is unlike the protocols in which forwarders do not choose the routing paths based on the least number of neighbors and, therefore, have higher interference.

There are a number of challenges associated with the design of interference and energy holes minimization routing protocols. The underwater medium carries unpredictable and severe conditions that challenge underwater communications. They include noise, mobility of sensor nodes with water, interference from underwater objects, shadow zones and attenuation of the desired signal [15][16]. Specifically, the movement of nodes with water currents challenges the communications among nodes. It is because it becomes difficult to locate the positions of nodes when they are not stationary. This becomes critically important in circumstances when nodes die and alive nodes have to replace their positions. This work addresses some of these challenges.

This chapter proposes the LF-IEHM protocol for UWSN. The protocol selects forwarder nodes by measuring the water pressure on them. Nodes in vicinity of water surface bear low water pressure and are given priority to route data. If two or more expected forwarder nodes have the same pressure levels, the response time is taken into account to choose the best forwarder. The response time is a measure of the distance of a forwarder node from source node. This strategy reduces the end-to-end delay and ensures that packets follow the shortest routes from source to destination. The proposed protocol uses variable transmission range of sensor nodes. A node can increase its transmission radius to find nearby nodes in situation when it does not find any node within its transmission range. This controls the energy hole problem and reduces packet loss. This strategy is particularly effective in sparse conditions.

Also, the proposed protocol is independent of nodes's position knowledge. In addition, the proposed protocol adjusts the holding time in a manner that minimizes simultaneous packets transmission by more than one node. This reduces interference that, in turn, further reduces packet loss. Moreover, unlike the conventional approach in UWSN that anchors few nodes at the bottom of the network, the proposed approach considers that every node can sense the attribute of interest and forward other nodes's data. This provides greater coverage area and flexibility in data sensing and transmission over the conventional approach.

5.2 Related Work

The scheme presented in [38] proposes a novel energy efficient protocol (NEFP) that selects forwarder nodes within a restricted zone from source to destination. Nodes that are close to the destination are given preference to take part in the routing process. The forwarding probability of a packet is also calculated along the expected routing path using Markov chains. The time for which a node holds a received packet is set so as to reduce interference. However, it requires the localization information of sensor nodes, which consumes surplus energy to locate the positions of nodes. Also, localization is difficult to achieve in underwater communications as currents in water cause the positions of nodes to change. In addition, nodes within the restricted forwarding zone die early due to frequent selection as forwarders. In order to avoid interference and reduce void hole formation, a routing protocol is proposed in [13]. The protocol selects forwarder nodes based on a cost function, which is calculated for every node by computing neighbor set, hop count and its distance form the sender. A sender node selects a forwarder node among its neighbors having the greatest value of the cost function. However, the cost function leads to increased delay and computation. The energy hole repairing depth based routing (EHRDBR) [83] considers the death of low depth nodes in the depth based routing (DBR) protocol. In DBR, the low depth nodes die early due to frequent selection as forwarders. This creates energy holes that badly affects transfer of packets to the ultimate destination. The EHRDBR detects an energy hole and replaces it with an alive node. This avoids the loss of data packets. However, detection of an energy hole and moving an alive node exactly to its position is cumbersome. It requires localization information, which is challenging in underwater communications. The dynamic source routing (DSR) protocol is modified in [22] to location aware source routing (LASR) that avoids interference and noise in underwater data routing. The LASR assumes that every node is aware of its position as it changes with water currents. While advancing packets to water surface, the paths with minimum noise and interference are chosen. However, the protocol has the shortcoming of calculating the positions of nodes. In addition, the position calculation interval is not dynamic. A forwarder node may change its position and move to another position before the sender node knows about it. This misleads the sender node and results in degradation of the system performance. The opportunistic void avoidance routing (OVAR) protocol forwards packets from source to destination using opportunistic routing [34]. The relay nodes are selected based on the successful delivery probability of a packet and packet advancement. However, the protocol involves the localization information of sensor nodes. It also suffers from the early death of nodes close to the water surface.

The routing algorithm designed in [20] considers a cylinder within which it forwards packets. The radius of the cylinder can be varied with respect to the packet loss probability, separation between sender node and sink and the corresponding threshold imposed on distance. The protocol improves transfer of packets to the end destination and energy expenditure. However, localization of nodes is required. In addition, when the network density is low, the protocol exhibits poor performance. The hydrocast protocol proposed in [33] uses depth based opportunistic routing along with dead and recovery method. The protocol themes to mitigate the interference and energy consumption in underwater data routing of nodes. The protocol uses recovery method to route data packets from a node that is within the void zone; node has no neighbors at all that have low pressure levels than the node itself. In this case, a recovery path is established from the node in the void zone through the route discovery method. In the route discovery method, node in the void zone forwards data packets to a node positioned to its side. The forwarder node then either greedily forwards the packet further or forwards it in the same manner to another sidewise neighbor. This process carries on until the packet reaches to the sink. However, the protocol suffers from early death of nodes due to opportunistic routing. The interference aware inverse energy efficient depth based routing (IA-IEEDBR) protocol addresses the minimization of interference in underwater routing [79]. The protocol routes data by selecting forwarder nodes having the lowest residual energy, the least number of neighbors and the least depth. However, selection of nodes with the lowest energy results in early death of such nodes that leads to significant packet drop as the network operates. The improved IA-IEEDBR (iIA-IEEDBR) protocol addresses the early death of low energy nodes in IA-IEEDBR protocol [80]. It divides the network into four logical sections with each section having a header that controls the death of nodes. Nodes bear random placement. However, the number of nodes in a single section is divided into two equal number of sleeping and sensing nodes. When a node dies in a logical section, the header node turns a sleeping node into a sensing node to avoid data loss. However, the header nodes are overloaded and their death collapses the performance of the entire network. Furthermore, transforming a sleeping node into sensing node when a node dies in a section does no guarantee the uninterrupted forwarding of data. It is because a node may die at a critical position and another node may be transformed into sensing node in a less critical position.

5.3 Channel Model

5.3.1 Channel Noise

The channel model involved in this scheme uses the same equations of noise and acoustic speed as discussed in Chapter 3. The attenuation associated with the channel is considered in the manner as given in [69] .

5.4 Proposed Protocol

5.4.1 The Proposed Network Model

The proposed network randomly deploys sensor nodes in a cube with 1000m length of a face. The sink is positioned on water surface at mid of the network as sketched in Fig. 5.1. Nodes are capable of communicating with each other through acoustic waves as radio waves

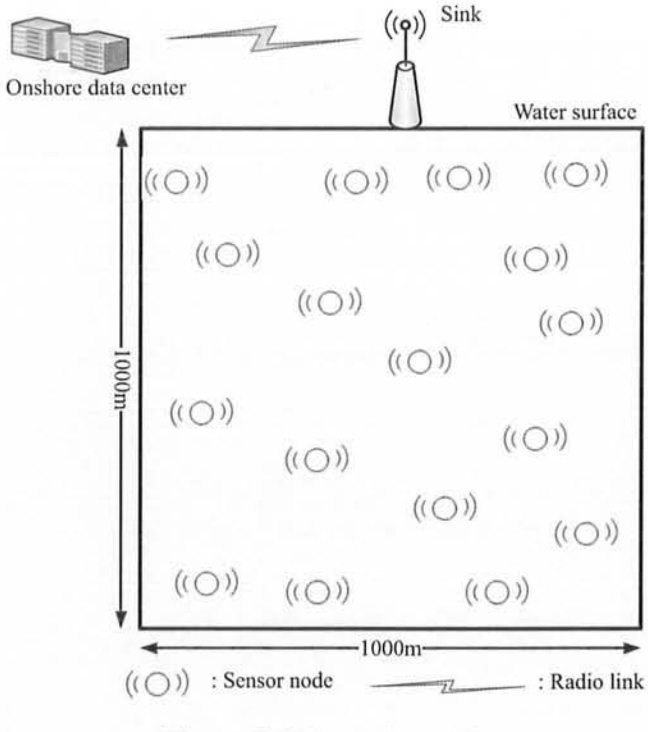

Figure 5.1 Network model.

are worse affected by water. The sink uses both acoustic and radio waves. It communicates with sensor nodes through the acoustic waves and with the onshore center through the radio waves. On account of greater speed of the latter, data that the sink receives is assumed as transferred to the terrestrial data center near the water surface.

5.4.2 Neighbors Determination

The random deployment of sensor nodes follows exchange of hello packets among them. Initially, just after deployment, nodes do not recognise their neighbors. For the identification of neighbors, every sensor node broadcasts a hello packet that contains its measured pressure level and unique ID. It waits for a certain time to hear from its neighbors: nodes that are within its transmission range. This waiting time is modeled by

$$\tau_w = \tau_p + \tau_{pr}, \tag{5.1}$$

where τ_w, τ_p and τ_{pr} represent the waiting time, propagation delay and processing delay, respectively. The extent of the propagation delay is dependent on mutual separation of transmitter-receiver pair and acoustic speed. The processing delay is an inherent parameter of the sensor design. It is a measure of the time difference between the reception of a hello packet to the initiation of the response to the original broadcaster. Being possessing the same characteristics, it is assumed that the processing delay is the same for all nodes.

Upon receiving a response from a neighbor, the broadcaster node initially gets the information about the neighbors pressure levels and IDs. It then constructs a table that contains its number of neighbors with their corresponding IDs and pressure levels. The table is broadcasted. Every node undergoes this process. In this way, a sensor node comes to know its multi-hop neighbors. When a broadcaster node does not hear back from any node within the waiting time, it sends the hello packet again and waits to receive a response from its neighbors. If it does not receive any response from its neighbors within the maximum waiting time, $max(t_w)$, it adaptively increases its transmission range to the maximum threshold and rebroadcasts the hello packet to include one or more neighbors as depicted by Fig. 5.2. In case (a), a sender node A intends for data transmission but there is no node within its transmission range. Nodes B, C and D are in proximity of its transmission range but not within it. Knowing this, node A increases its transmission range until node B lies within its range (becomes its neighbors) as shown in case (b).

The transmission range is always increased to the maximum threshold independent of how many new nodes lie in it. Node A (and every other sensor node) declares no neighbor at all when the maximum number of rebroadcasts are reached with no neighbor at all even after increasing the transmission range. The neighbor finding process is repeated after regular

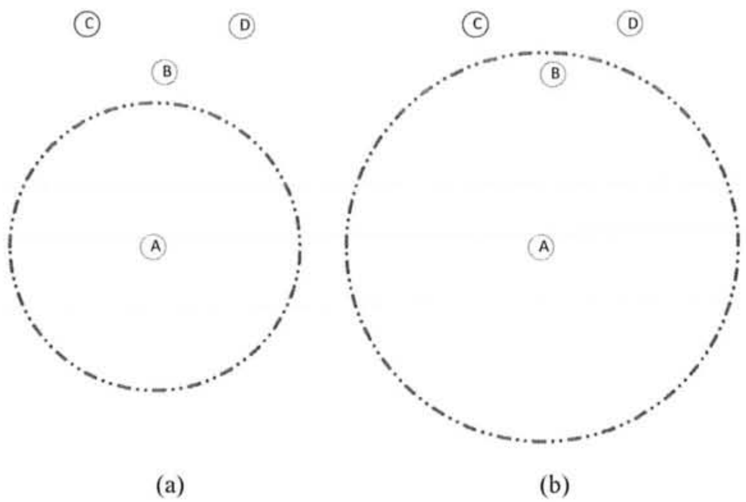

Figure 5.2 Adaptively covering the absence of neighbors(a): No neighbor is there for node A. (b): Transmission radius of A increases to have neighbors.

intervals of time as nodes die due to their limited battery life and change their positions with water currents. This ensures that data is forwarded to alive neighbors that reduces the probability of packets loss.

5.4.3 Packet Forwarding

As soon as a sensor node is ready to initiate data transmission, it chooses the best forwarder among its neighbors by looking into the routing table. A best forwarder has the lowest pressure level. The ID that represents the best forwarder is embedded by the sender node in data packet and forwards it. All its neighbors receive it. Every neighbor matches its own ID with the ID of the best forwarder in the data packet. The intended forwarder node accepts the packet for further transmission towards the sink. All the rest of the neighbors simply discard it due to mismatch of the IDs. The continuation of this process either transfers packets to the ultimate destination or drops it when no the link is not free within the preset time. If a sender node has two or more forwarder nodes with the same pressure levels, the response time is taken into account to select the best forwarder. In such a case, the best forwarder has the lowest pressure level and the shortest response time.

The Algorithm 5.1 shows the selection of the best relay. A sender node i chooses the best relay node j among its set of neighbors N_i with lowest pressure level $min(p_j)$ or with lowest pressure level and shortest response time $min(p_j, \tau_w)$.

Algorithm 5.1 The Best Relay Selection

$BR \leftarrow$ the best relay
$p_j \leftarrow$ pressure level of a relay node j
$R \leftarrow$ A node transmission radius
$E \leftarrow$ energy of node
$N_i \leftarrow$ nodes in neighborhood of a source node i
$N_j \leftarrow$ nodes in neighborhood of a relay node j
$M \leftarrow$ network total nodes
for $i = 1:1:M$ **do**
  if $E_i > 0 \;\; \& \;\; E_j > 0 \;\; \& \;\; j \in N_i$ **then**
    $BR_i = argmin_{j \in N_i}(p_j) \;\; OR \;\; argmin_{j \in N_i}(p_j, \tau_w)$
  else
all nodes are dead
  end if
end for

5.4.4 Packet Holding Time

Upon reception of a data packet by an intended suitable forwarder j from a sender node i, it holds it for a preset interval of time called the packet holding time τ_h. This time depends upon the number of neighbors N_j of the forwarder, the pressure difference between the sender and forwarder $p_i - p_j$, the speed of acoustic wave c and the ratio of the initial energy level E_0 to the current energy level E_c. Mathematically, it is written as

$$\tau_h = \frac{N_j(p_i - p_j)}{c(\frac{E_0}{E_c})}. \tag{5.2}$$

The packet holding time modeled above ensures that a packet reaches from source to destination with small delay, low interference and low probability of loss. Its dependency on the pressure difference ensures that low depth nodes close to the surface of water hold packets for small time as these nodes are often overburdened by the nodes in the bottom. This increases the probability of successful packets transmission towards the sink by reducing overloading of these nodes by data packets. If such nodes hold the packets for long time, it results in overloading and congestion that finally will result in packet loss. Also, a forwarder node having smaller number of nodes in its neighborhood will hold the packet for a shorter time than a node with greater neighbors. It is because the former faces less interference (less neighbors) than the latter (more neighbors). Furthermore, the ratio $\frac{E_0}{E_c}$ is smaller for a nodes with higher current energy level than a node with smaller value of current energy level. Therefore, nodes with greater values of current energy levels hold the packets for longer time as these nodes have enough energy to remain alive in the network. A node holds a packet and senses the channel to become free for packets transmission. In case the channel is found

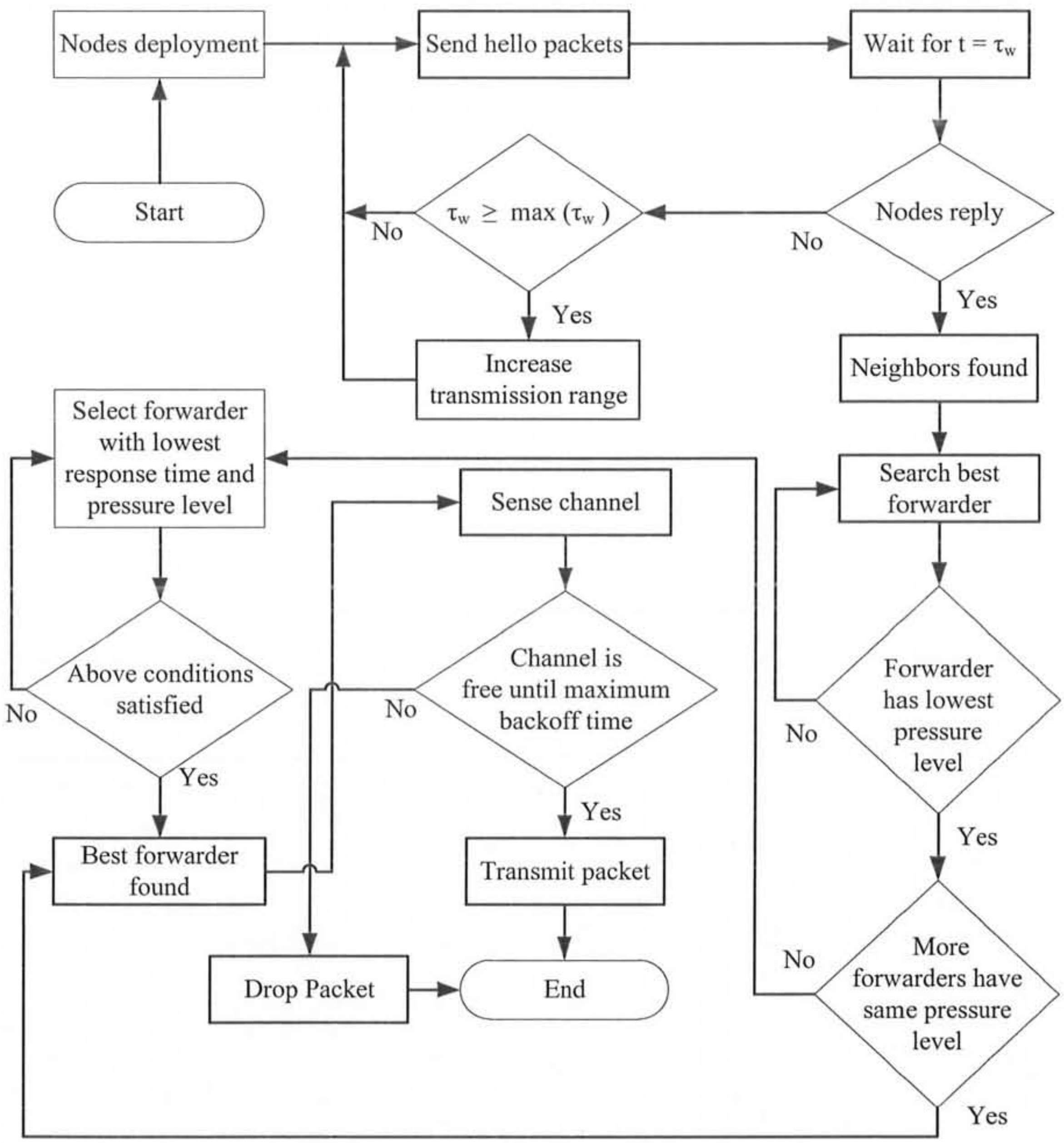

Figure 5.3 LF-IEHM flow chart.

to be not free, the node backs off. The packet is ultimately dropped when the maximum back off time is reached. Fig. 5. 3 depicts flow chart that shows how the proposed scheme proceeds in transferring packets to ultimate destination.

5.5 Simulation Results

A network with dimensions $1000m \times 1000m \times 1000m$ is supposed that deploys 200 nodes in a random fashion. The communication radius a node has is fixed at 300m. The maximum transmission radius to avoid energy holes is 450m. The rate of data transmission is 10 kbps and a single packet sizes to 50 bytes. The amount of power that a single node consumes in transmitting and receiving mode is 8 and 0.8W, respectively. The consumed power in the idle state is 8mW. The proposed scheme is compared with EHRDBR and NEFP protocols. It is due to the reason that EHRDBR involves the mechanism of addressing energy holes that our scheme also takes into account. The NEFP protocol addresses the interference that our scheme also considers. In addition, the EHRDBR considers multiple sinks at the water surface while the proposed scheme considers only one. Therefore, for the sake of fair comparison, one sink at the top middle surface is considered in all the three protocols. Moreover, unlike the EHRDBR that considers two sensing nodes at the bottom of the network, the proposed simulation setting takes into account the capability of every node in sensing the parameter of interest. This provides greater coverage area to the network as required by the real world underwater applications.

Following the DBR protocol, the random walk mobility model is considered to take into account the movements of sensor nodes with water currents. The MAC layer implementation is accomplished using the scheme given in [76].

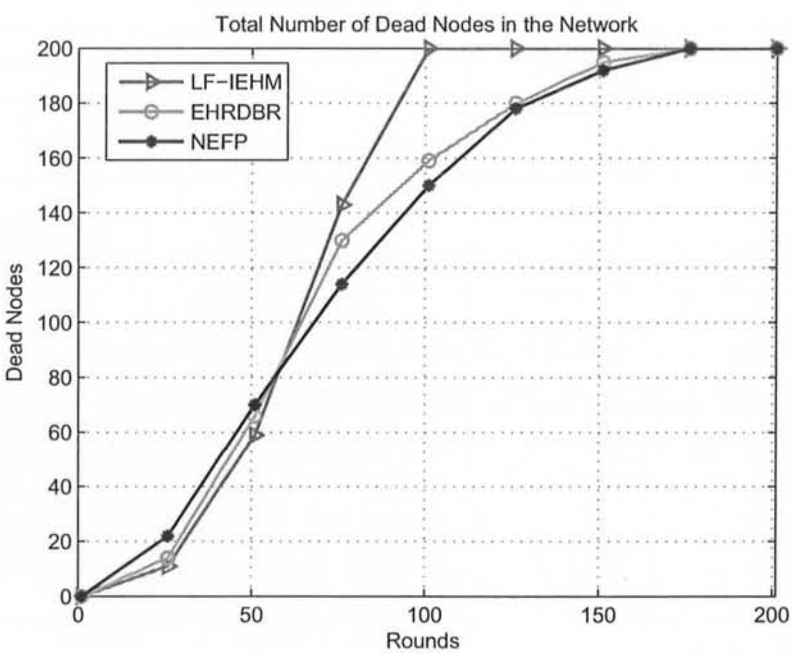

Figure 5.4 Dead nodes.

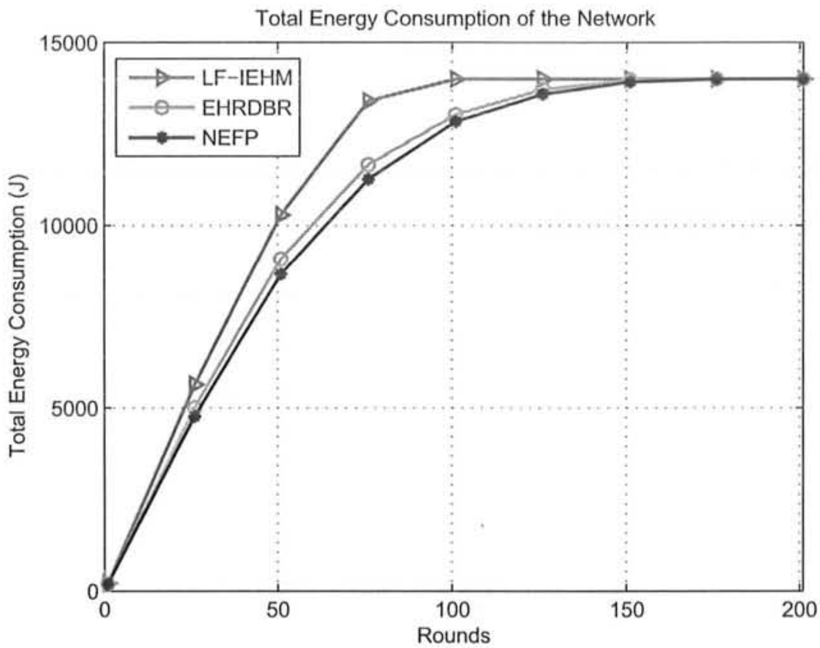

Figure 5.5 Energy expenditure.

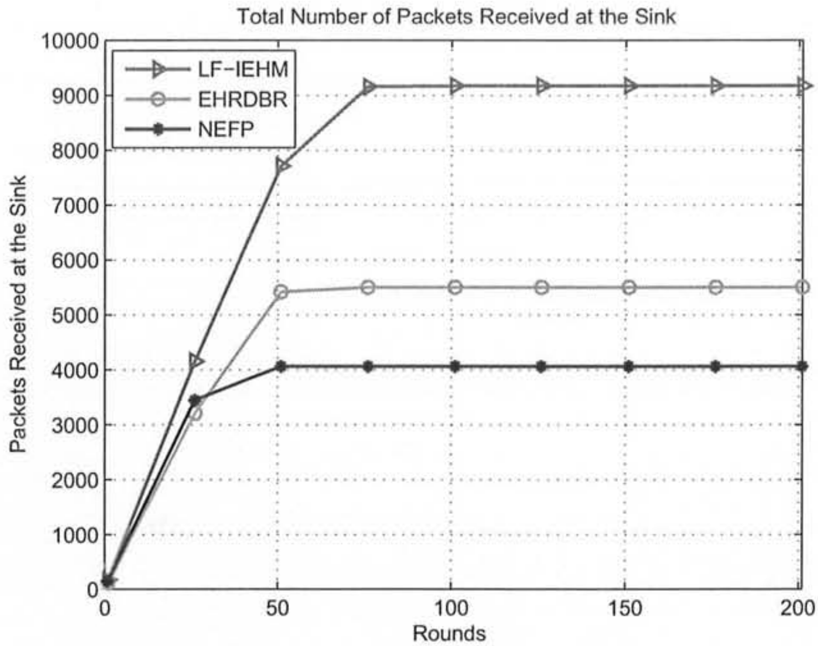

Figure 5.6 Packets reaching the sink.

Fig. 5.4 depicts the patterns with which nodes die in the network. For almost first 58 rounds, the rate of nodes death is the slowest in LF-IEHM. The reason is that more alive

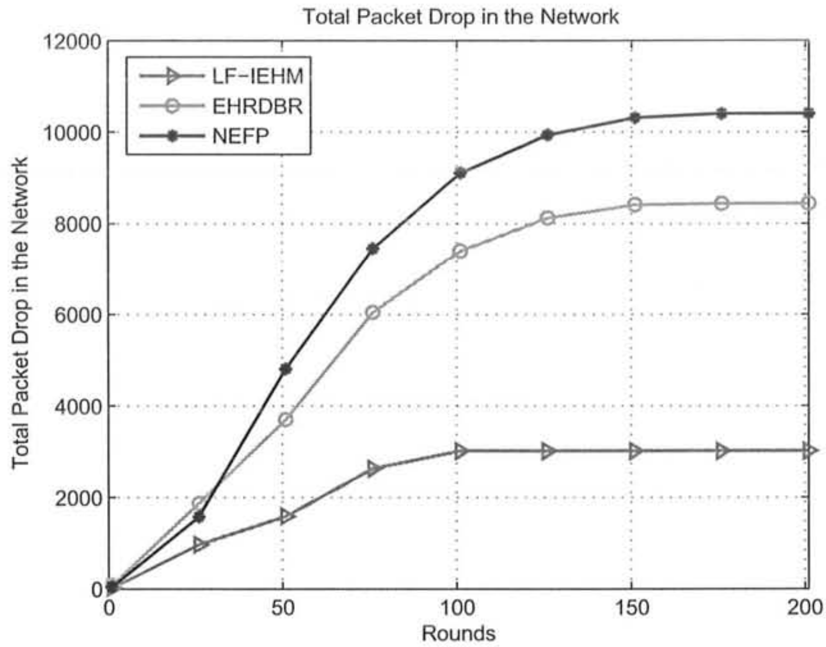

Figure 5.7 Packet drop.

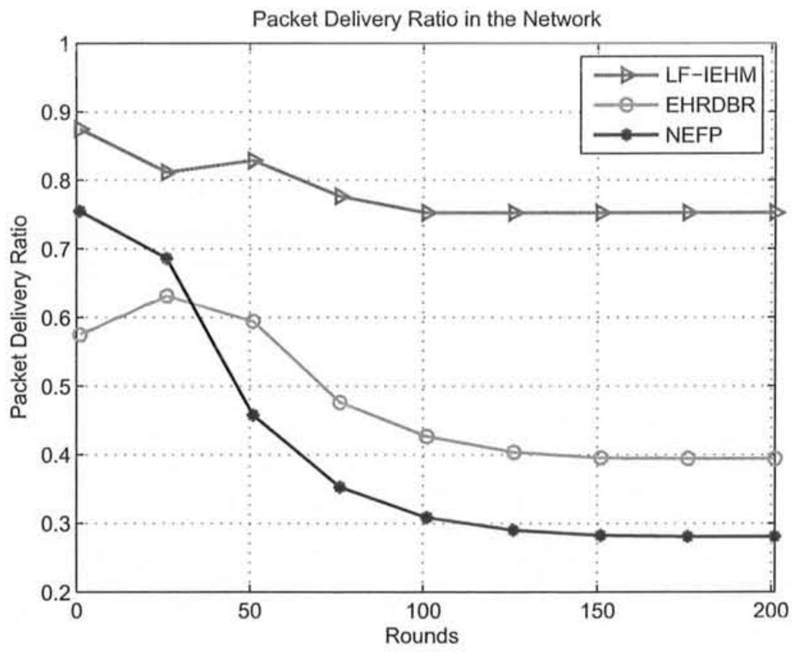

Figure 5.8 Delivery ratio of packet.

nodes are present. This allows a sender node to select forwarder nodes within its normal transmission range consuming less energy. As rounds progress, nodes start dying, especially nodes close to the water surface with low pressure level. This causes formation of energy

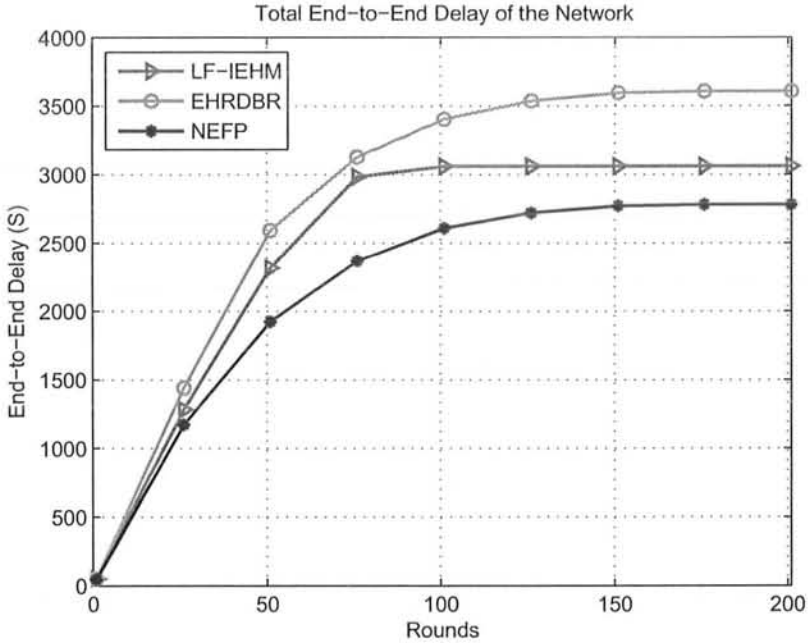

Figure 5.9 Network latency.

holes that results in packet drop. In order to overcome these energy holes, a sender node in LF-IEHM increases its transmission range. This results in more energy consumption by nodes. As a result, after 50 rounds, the rate of nodes death becomes the fastest in LF-IEHM. The rate with which nodes die in NEFP is the fastest for almost the first 58 rounds. It is because the NEFP selects forwarders close to the water surface (the sink) and within a restricted zone. Such nodes are selected frequently for data forwarding that makes them depleted of the battery power. Following this, the rate with which nodes die in EHRDBR becomes more rapid than NEFP due to the death of low depth nodes in EHRDBR that are overburdened plus the extra cost of energy hole repairing.

Fig. 5.5 shows the behavior with which energy is consumed by nodes. All the protocols exhibit similar pattern of energy expenditure for the first several rounds. It is because more forwarder nodes are available to route data along the best available paths in all the protocols. After that, nodes start to die and the best available paths are no longer available. Following this, a node transmission radius is increased in LF-IEHM consuming more power to find forwarder nodes. This leads to the highest energy consumption in LF-IEHM. The curve of consumed energy of LF-IEHM shows remarkable deviation from the corresponding curves of EHRDBR and NEPR protocols between the 22 to 100 rounds. This means LF-IEHM consumes energy with the fastest rate in this interval of rounds because nodes start to consume more power by increasing their transmission range to forward packets. Energy consumption is higher in EHRDBR than NEFP due to redundant packets transmission and extra cost of energy hole repairing in the former. Fig. 5.6 shows reception of packets at sink. Due to the variable transmission range, the highest amount of packets are transferred to the end destination in LF-IEHM. In LF-IEHM, when a sender node does not find any neighbor, it increases its transmission range to include one or more forwarder nodes. Due to this, a packet has high chance to reach surface. As a result, LF-IEHM has the highest amount of transferred packets to sink as compared to EHRDBR and NEFP where every node has a fixed transmission range.

The plot shown in fig. 5.7 shows the behavior by which nodes drop packets. Due to variable transmission range and interference mitigation strategy, the LF-IEHM has the lowest packet drop. Initially, packet drop is smaller in NEFP than EHRDBR due to forwarding packets in the restricted paths based on the forwarding probability. This approach routes packets along the shortest paths towards destination and avoids it over unnecessary paths. This, in turn, minimizes packet drop probability. However, forwarder nodes die soon along the restricted paths in NEFP due to frequently forwarding of data. At the same time, when nodes start dying in EHRDBR, its energy hole repairing mechanism replaces energy holes with alive nodes. Also, redundant packets transmission in EHRDBR reduces the probability of packet drop. In essence, packets drop decreases in EHRDBR and increases in NEFP in later rounds.

The ratio showing delivery of packets is depicted in Fig. 5.8. Following the behavior of delivery of packets and drop, the delivery ratio is the highest for LF-IEHM. The delivery ratio is higher for NEFP than EHRDBR for the first several rounds but decreases as rounds progress due to death of nodes in the restricted forwarding zone in NEFP and energy hole repairing and redundant packets transmissions in EHRDBR. Fig. 5.9 shows the plot of network latency. Due to forwarding in the restricted forwarding zone from source to destination, NEFP has the smallest delay. In EHRDBR, a sender node selects forwarder nodes using a depth threshold. This causes the greatest delay in EHRDBR.

This chapter proposes the LF-IEHM protocol for UWSN. A node ready for initiation of packets transmission selects a relay in its neighborhood that bears lowest pressure of water. If two or more forwarder nodes have the same pressure levels, the response time is taken into account to decide the best forwarder; forwarder with the lowest pressure level and having the shortest response time is chosen as a forwarder. When a sender node does not find any neighbor node, it increases its transmission range to include one or more forwarder nodes. This overcome packet loss due to absence of forwarder nodes. Also, the packet holding time is defined for every node in a manner to minimize simultaneous transmission of data packets by two or more nodes. This reduces interference during packet forwarding. The proposed protocol has superior performance as compared to the counterpart schemes in transferring packets to the end destination.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis explores the characteristics of UWSN and proposes routing protocols for mitigating interference due to packets transmission and collision. The fundamental objective this research has is the development of a foundation for devising novel and advanced routing protocols for UWSN.

Chapter 1 started with the background information of underwater wireless sensor networks, their challenges, applications, issues in current routing protocols, advantages of interference aware routing protocols and the proposed protocols. Chapter 2 reports some current routing protocols in UWSN. The problems that these protocols address at the expense of the compromised parameters are also highlighted.

Chapter 3 describes the proposed EEIRA protocol that copes with interference due to packet collision and packet forwarding. The network is divided into three regions to differentiate source, relay and destination nodes. In this protocol, a node ready for sending data, accomplishes the selection of a forwarder node in its neighborhood with the shortest distance to end destination and the least number of neighbors. Based on simulation results, the proposed protocol reveals promising performance in sending more packets to the sink while reducing energy consumption with lower latency than some prevailing schemes.

Chapter 4 discusses the localization free EEIAR protocol to cope with interference due to packets forwarding. The network is divided into three segments for differentiating among the nodes that sense, relay and receive data at destination. A relay is the one possessing the least count of neighbors and lowest pressure of water. The proposed protocol outperforms some prevailing techniques in transferring packets to ultimate destination and energy expenditure.

Chapter 5 describes the LF-IEHM protocol. A node having data ready for transmission chooses its neighbor node with the lowest pressure of water on it. If two or more neighbor nodes have the same pressure levels, the neighbor having the response time as the shortest among the neighbors is considered for data forwarding. When a sensor node does not find any neighbor node, it increases its transmission range to include one or more neighbor nodes. This overcomes packet loss due to the condition when a node has no neighbor nodes in its normal communication range. An algorithm is also proposed to adjust the holding time of nodes to avoid packets transmission at the same time and overcome the resulting interference. Accomplishing extensive simulations, the devised algorithm shows promising performance in terms delivery of packets to end destination at the expense of greater energy consumption than some prevailing algorithms.

6.2 Future Work

1. As shown in Fig. 3.4 and Fig. 4.6, the rate at which nodes die in proposed algorithms is the slowest, this rate can be made further slower for applications that require long term operation of nodes. They include, for instance, water quality detection, environmental monitoring, disaster detection and underwater scientific exploration. This can be accomplished by introducing mobile sink nodes or autonomous underwater vehicles (AUVs). This may ensure that the nodes transfer packets to these devices. This will bring further reduction in energy expenditure and, therefore, nodes will remain alive for longer time within the network. The AUVs easily remain at the surface of water so it is easy to power them. This make the proposed schemes energy efficient in conditions, where nodes have data packets but do not find forwarders. In addition, the mobility of nodes with water currents is addressed with these devices.

2. The interference avoidance with cross layer approach is also a future direction of study for the proposed protocols. The MAC layer transport of data packets can be made intelligent to transfer the desired packets and avoid redundant packets transmission. Furthermore, interference, shadow zones and connectivity problems due to underwater objects can be addressed and incorporated.

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