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ENHANCED HOP-BY-HOP ROUTING ALGORITHMS FOR UNDERWATER ACOUSTIC SENSOR NETWORKS

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This thesis work is dedicated to my parents and my teachers throughout my education career who have not only loved me unconditionally but whose good examples have taught me to work hard for the things that I aspire to achieve.

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”All praise to Allah, the lord of the worlds, and His Prophet Muhammad (peace be upon him), his family and his companions.”

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ABSTRACT

Underwater Acoustic Sensor Network (UW-ASN) is a wireless network infrastructure applicable in deep ocean to sense, collect and transmit information to seashore data collector. Underwater sensor network consists of sensor nodes disposed in different depths, equipped with a low bandwidth acoustic modem and acts collaboratively to route the packet from one node to another. Underwater routing protocols provide route information to underwater sensor nodes to transmit collected information efficiently using an optimal path. Routing protocol related to UW-ASN is identified with the issues of low energy consumption, high end-to-end delay and shorter network lifetime. These are due to the distribution of unnecessary information packet flooding in route establishment, improper selection of next hop neighbour and inefficient routing path generation. This research develops a routing protocol that will be able to control flooding of hello packet at information distribution phase, to calculate link quality and composite metric cost for next hop selection and to regularly update the energy status in order to achieve optimum balance in routing path. The developed protocol is called Distance based Reliable and Energy Efficient (DREE) consists of three schemes. The first scheme is called distance calculation and information distribution scheme that calculates the distance between potential neighbours and distribute the local information in an energy efficient manner. The second scheme is route planning and data forwarding scheme in which a node calculates the link quality towards its neighbours and selects a path based on physical distance, link quality and node energy information. Finally, the third scheme is energy balancing scheme that provides each node with new energy status of its neighbours on regular basis. DREE is compared with a Reliable and Energy Efficient routing protocol (R-ERP^{2}R) and Depth based Routing (DBR) protocol. Simulation shows that DREE reducing energy consumption in the information distribution phase by 187% and 179% compared to R-ERP^{2}R in random and grid topology respectively. DREE achieves higher packet delivery ratio of 96% with a similar end-to-end delay as R-ERP^{2}R. DREE improves packet delivery ratio by 7% and 13% over R-ERP^{2}R and DBR, with 9.3% and 201% less energy consumption respectively in data forwarding phase. Finally, DREE improves network lifetime by 18% and 74.5% compared to R-ERP^{2}R and DBR protocols.

ABSTRAK

Rangkaian Penderia Akustik Dalam Air (UW-ASN) adalah infrastruktur rangkaian tanpa wayar diaplikasikan dalam lautan dalam untuk mengesan, mengumpul dan menghantar maklumat ke pengumpul data di tepi pantai. Rangkaian penderia dalam air mengandungi nod penderia disusun dengan kedalaman yang berbeza, dilengkapi dengan model akustik yang rendah lebar jalur dan bertindak secara kolaboratif untuk menghala paket dari satu nod ke nod yang lain. Protokol penghalaan dalam air perlu menyediakan maklumat halaan kepada nod deria dalam air untuk menghantar maklumat terkumpul secara efisien menggunakan laluan yang optima. Protokol penghalaan berkaitan dengan UW-ASN dikenal pasti mengalami isu-isu seperti penggunaan tenaga yang rendah, tangguhan hujung-ke-hujung yang tinggi dan hayat rangkaian yang pendek. Ini adalah disebabkan oleh pengagihan kebanjiran paket maklumat yang tidak perlu semasa pemantapan halaan, pemilihan hop jiran seterusnya yang tidak tepat dan penjanaan laluan penghalaan yang tidak efisien. Penyelidikan ini membina protokol penghalaan yang mampu mengawal kebanjiran paket hello semasa fasa pengagihan maklumat, yang boleh mengira kualiti sambungan dan kos metrik komposit untuk pemilihan hop seterusnya dan yang dapat mengemaskini secara berkala status tenaga untuk mencapai imbangan yang optima dalam laluan penghalaan. Protokol yang dibangunkan dipanggil Boleh percaya dan Cekap Tenaga berasaskan Jarak (DREE) mengandungi tiga skema. Skema pertama dipanggil skema pengiraan jarak dan pengagihan maklumat yang mengira jarak antara jiran-jiran yang berpotensi dan mengagihkan maklumat tempatan dalam bentuk cekap tenaga. Skema kedua adalah skema perancangan laluan dan pemajuan data di mana nod mengira kualiti sambungan ke arah jiran-jirannya dan memilih laluan berdasarkan jarak fizikal, kualiti sambungan dan maklumat tenaga. Akhirnya, skema ketiga adalah skema imbangan tenaga yang menyediakan kepada setiap nod status tenaga jiran-jiran barunya secara berkala. DREE dibandingkan dengan protokol penghalaan Tenaga Efisien (R-ERP^{2}R) dan protokol Penghalaan Berasaskan Kedalaman (DBR). Simulasi menunjukkan DREE mengurangkan masing-masing penggunaan tenaga semasa fasa pengagihan maklumat kepada 187% dan 179% dibandingkan dengan R-ERP^{2}R dalam topologi rawak dan grid. DREE mencapai kadar penghantaran paket yang tinggi iaitu 96% dengan tangguhan hujung-ke-hujung sebagaimana R-ERP^{2}R. DREE meningkatkan kadar penghantaran paket kepada 7% dan 13% ke atas R-ERP^{2}R dan DBR dengan mengurangkan masing-masing 9.3% dan 201% semasa fasa pemajuan data. Akhirnya, DREE meningkatkan hayat rangkaian sebanyak 18% dan 74.5% berbanding dengan protokol R-ERP^{2}R dan DBR.

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2H-ACK	-	Two Hop Acknowledgement
AODV	-	Adhoc On-demand Distance Vector
APCR	-	Adaptive Power Control Routing
ARQ	-	Automatic Repeat Request
ASL	-	Asymmetric Link
AUV	-	Autonomous Underwater Vehicle
BER	-	Bit Error Rate
CARP	-	Channel Aware Routing Protocol
DBR	-	Depth Based Routing
DBRS	-	Distance Based Routing Scheme
DCR	-	Depth Controlled Routing
DESERT	-	DEsign, Simulate, Emulate and Realize Test-beds
DFR	-	Dynamic Flooding-based Routing
DREE	-	Distance based Reliable and Energy Efficient
DSR	-	Dynamic Source Routing
DV-hop	-	Distance Vector hop
DY-NAV	-	Dynamic Network Allocation Vector
ETX	-	Expected Transmission Count
FDBR	-	Fuzzy Depth Based Routing
FLQE	-	Fuzzy Logic Based Link Quality Estimator
GPNC	-	Geographical routing based on Partial Network Coding
GPS	-	Global Positioning System
H^2-DAB	-	Hop-by-hop Dynamic Addressing Based
ICRP	-	Information Carrying based Routing Protocol
ISO	-	International Standards Organization
L2-ABF	-	End-to-End Delay and Energy Efficient Routing Protocol

LOARP	-	Low Overhead Routing Protocol
MAC	-	Medium Access Control
MRP	-	Multilayer Routing Protocol
NS2	-	Network Simulator 2
OFDM	-	Orthogonal Frequency Division Multiplexing
OSI	-	Open System Interconnection
OTcl	-	Object-oriented Tool Command Language
PRR	-	Packet Receive Ratio
PTMAC	-	Pipeline Transmission Medium Access Control
QELAR	-	Machine Learning based Adaptive Routing
RDBF	-	Relative Distance Based Forwarding
R-ERP^{2}R	-	Reliable and Energy Efficient Routing Protocol
RF	-	Radio Frequency
RSSI	-	Receiver Signal Strength Indicator
SF	-	Stability Factor
SNR	-	Signal-to-Noise Ratio
SPRR	-	Smoothed Packet Receive Ratio
SUN	-	Source Routing Protocol for Underwater Networks
TCP/IP	-	Transmission Control Protocol/Internet Protocol
TDoA	-	Time Difference of Arrival
ToA	-	Time of Arrival
TWSN	-	Terrestrial Wireless Sensor Networks
UDP	-	User Datagram Protocol
UW-Aloha	-	Underwater Abramsons Logic of Hiring Access
UW-ASN	-	Underwater Acoustic Sensor Network
WOSS	-	World Ocean Simulator System

LIST OF SYMBOLS

α	-	Normalization symbol or smoothness factor
β	-	Normalization Symbol for link quality estimation
$\mu(i)$	-	Represents membership function for high quality links
δt	-	Represents high precision time

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CHAPTER 1

INTRODUCTION

1.1 Overview

Underwater acoustic sensor network (UW-ASN) is an emerging area of research because of its applicability of monitoring, navigation, surveillance and tracking applications in various environmental, industrial and military domains. The increasing interest in these applications motivates research for development of underwater routing protocols in acoustic medium. Multiple underwater routing protocols have been proposed over the years that provide suitable low overhead mechanisms to sense, collect and transmit sensed information to onshore control systems. However, the intrinsic conditions in underwater environment raises many challenges for the design of reliable and efficient routing protocol. The motivation behind this research is to address the problem of high energy consumption in the information distribution phase, the problem of high end-to-end delay in route planning and data forwarding phase and finally the problem of enhancing network lifetime that has a significant effect on the performance of the network.

1.2 Motivation

The oceanic world has been fascinating humans for many centuries and has been a tremendous source of aliment, mean of transportation and also hold loads of natural resources (such as salt, natural gases, coal mines) in it. Since water plays a vital role in human's survivability, with the advancement of science and technology it was only in last century humans seriously started the exploring underwater world, which was inadequate before. Water covers 71% of earth surface and nearly 10% has been scrutinized (Ayaz *et al.*, 2011). Oceans play an important role in climatic change over the land occupied by humans and hence its investigation is important to understand the causes of natural events like hurricanes, sea storms, tsunami's, etc. However, due to stringent oceanic environment (such as high water pressure, extreme temperatures) and other uncertain events, unmanned exploration with self-configuring and communicating capabilities is inevitable. Hence, unmanned exploration gives rise to the use of automated underwater sensor network technology and underwater communication protocols.

Underwater routing protocols play a vital role in sensing, collecting and transmitting sensed information from underwater sources and then delivering this information to the onshore data collection centre. However, underwater network routing protocols requires exhaustive research work to improve their performance. Underwater networks have many applications in the modern world such as oil/gas exploration, pollution monitoring, measuring of seismic activities for disaster prevention, navigation support for ships and intrusion detection. These applications are in great demand but require further enhancement in this technology to work properly and to collect data in an effective way.

1.2.1 Underwater Scenario Environment

Different architectures and node deployment strategies for underwater sensor network have been presented in literature such as Al-Bzoor *et al.* (2013); Climent *et al.* (2012); Ibrahim *et al.* (2013b) and Yadav *et al.* (2014). These deployment methods can be classified into two broad categories (i) classification with respect to motion such as stationary, mobile or hybrid nodes or (ii) classification with respect to coverage space such as 2D or 3D (Zeng *et al.*, 2013). Underwater acoustic wireless sensor networks are formed with multiple sensor nodes as shown in Figure 1.1 (Heidemann *et al.*, 2012). Some nodes are tied using the wire at the bottom of the ocean with anchors but can move up to the length of the wire they are connected and are called anchor nodes. Anchor nodes and autonomous underwater vehicles (AUV) are used to collect information from a specific areas and very helpful in providing localization information or to be used as a reference point to the nodes. Ordinary sensor nodes are deployed underwater in most of the scenarios and move freely underwater along with water currents. However, some underwater routing protocols such as Information carrying based routing protocol (ICRP) proposed by Liang *et al.* (2007) make use of fix ordinary sensors nodes as well. The job of these ordinary nodes is to sense, collect and transmit the sensed information in the direction of the sink with the help of acoustic modems. Sink nodes are floating nodes and are deployed at the water surface;

However in some scenarios sink nodes are stationary (Yan *et al.*, 2008). Sink nodes are usually equipped with acoustic and radio modems. Radio modems provide inter sink and communication with onshore control centre, whereas acoustic modems are used to communicate with ordinary underwater nodes. Onshore data collection centre make use of terrestrial or satellite communication to send further collected data to an offshore data centre for data analysis.

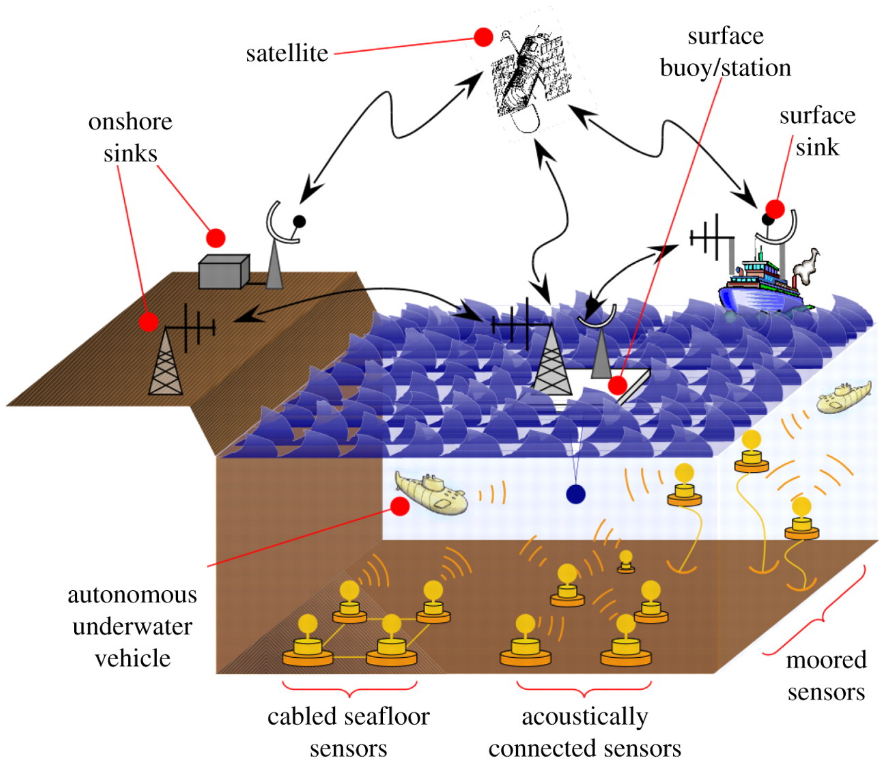

Figure 1.1: Different types of node deployment in UW-ASN

All these different sensor nodes must work together in the form of an organized network, as the set goals/objectives depend upon their collective performance. Hence, the communication schemes require a change in their way of operation to work in collaboration and efficiently in underwater networks.

1.2.2 Applications of UW-ASN

Underwater sensor networks are considered a promising solution for the applications, where different sensor nodes adapt with the complexities and challenges posed by extreme underwater environment and work together to achieve their goals. A brief summary of some of these applications is given below:

i. *Disaster Prevention:* Underwater sensor networks can be used for disaster prevention applications from generation to their behavior such as sea quakes, sea storms and tsunami that help provide warnings to coastal areas.

ii. *Environmental oceanic Monitoring:* Underwater sensor networks facilitate in monitoring water currents, changes in the maritime environment, improving weather forecasts and can help develop human activities and provide study of their effect on marine echo systems (Akyildiz *et al.*, 2005). Moreover, monitoring of chemical, biological and nuclear pollution and tracking/study of the aquatic species are typical applications for which UW-ASN is assumed to be a promising solution. Furthermore, studies by Zhang *et al.* (2004) also describe applications for areal detection of certain micro-organisms. One of the common and most important application in the modern world is oil/gas pipeline safety and leakage detection, as a security risk and monitoring importance increases with increase in length of pipe that is mostly over couple of miles underwater (Jawhar *et al.*, 2007).

iii. *Underwater Exploration:* Underwater sensor networks have applications in mine, mineral and oil/gas reservoir detections underwater. Moreover, they can also be used in long digital data transfer optical cables and oil/gas pipeline monitoring and deployment.

iv. *Oceanic Sampling:* Synoptic and cooperative sampling of 3D ocean environment can be done in underwater networks assisted with AUV's.

v. *Tactical Surveillance and Targeting:* Underwater sensor networks assisted with AUV's can perform tactical surveillance, targeting and intrusion detection in the 3D underwater environment. According to Akyildiz *et al.* (2005), underwater surveillance shows better results over traditional terrestrial radar systems for low signature targets.

vi. *Assisted Navigation:* Underwater sensor networks are supportive in submarine and ships navigation and help to provide safe passage in the presence of hazards and assist in locating underwater rocks and shoals (i.e. sandbanks and ridges).

1.2.3 Constraints in UW-ASN

Terrestrial wireless sensor networks (TWSN) make use of radio waves for communication but in underwater networks these radio waves at high frequency are prone to absorption but could propagate at ultra-low frequencies ranging between 30 - 300 Hz (Akyildiz *et al.*, 2004). Using radio waves at low frequencies require large directional antenna's and high transmission power. On the other hand, optical communication is subject to scattering and not a good choice for long distance communication in the underwater environment (Akyildiz *et al.*, 2004). However, up to several Mbits/sec could be achieved with optical modems in crystal clear water but for short range connections (Fair *et al.*, 2006). Therefore, acoustic waves mostly are considered preferred method of communication for the underwater networks. Acoustic channel is considered a reliable communication medium for short range, adhoc and cost efficient UW-ASN. Despite a preferred choice, underwater acoustic channels are considered new and pose a whole lot of new communication challenges at broad level. Underwater sensor network channels can be classified as vertical and horizontal channels. However, horizontal channels are considered to have posed with significant challenges like signal absorption, multipath effect due to moving obstacles causing frequency selectivity, noises generated by natural events or man-made devices, large delays and signal scattering due to reflections that result in temporal signals (Sameer *et al.*, 2012). Moreover, it is also been shown that the increase in frequency in the acoustic channel results in increased attenuation due to absorption of high frequency components underwater. For example at frequency of 12.5 kHz, the amount of absorption is 1 dB/km, while at frequency of 70 kHz, it is more than 20 dB/km (Heidemann *et al.*, 2006).

On the other hand, low frequencies are dependent upon ambient noise, which limit the available bandwidth. Hence, in both cases low bit rate is the outcome which is significantly low as compared to radio networks (Akyildiz *et al.*, 2004). Beside that, propagation of sound waves in underwater environment are contingent on the physical characteristics of underwater environment such as density, pressure, temperature and salinity of water that further degrades the performance of acoustic channels (Heidemann *et al.*, 2006). Furthermore, acoustic waves travel at the speed of 1500 m/s underwater which is slower than radio waves in air by five orders of magnitude and vary spatially with above said physical characteristics (Heidemann *et al.*, 2012). Furthermore, delay increases with the rise in distance between communicating nodes, resulting in time-varying frequency shifts and spreading of frequency, resulting in Doppler variance of received signal. Delay in underwater networks is 0.67 km/s, which is five order of magnitude lower than radio networks (Akyildiz *et al.*, 2004). This variation in acoustic signals gives rise to the phenomenon of refraction, which together with multipath results in poor reception and in some places lead to shadow zones (Partan *et al.*, 2007) that complicates the interpretation at the receiver. Together these constraints result in communication channel of poor quality and high latency, thus combining the worst aspect of terrestrial mobile and satellite radio channel into communication medium of extreme difficulty. Therefore, while designing routing protocols for incorporating the limitations posed by acoustic medium must be considered for the efficiency of the protocol. The change in the communication medium from radio channels to acoustic channels make traditional wired and wireless routing protocol unsuitable, which result in poor performance.

Therefore, challenges enforced by undersea environment requires the new set of routing protocols and algorithms that can cope up with its harshness and provide effective communication. The challenges imposed by the underwater environment are:

i. *Node Mobility:* Multiple applications require free nodes that are not anchored at the bottom or fixed at the surface. In this situation, nodes move both in vertical and horizontal direction with water currents, especially in shallow water. However, vertical movement is not significant (Cui *et al.*, 2006). This phenomenon results in communication gaps/voids and often requires autonomous underwater vehicles (AUV's) for retrieving the location of separated nodes and help in adjusting their position for data routing. Although node movement is helpful in the vast coverage area in sparse networks as a data mule and providing connectivity among nodes but also result in overhead and require movement prediction models for improved efficiency.

ii. *High Bit Error Rate:* Acoustic channels have limited bandwidth and multiple channel impairments like multi-path, fading and noise. Therefore, the error rate is very high and frequent disconnections are common as compared to terrestrial sensor networks and the error rate increases with the increase in distance between the nodes.

iii. *Communication Range:* Communication range in underwater networks is inversely proportional to the bandwidth, which means that increase in range results in very limited bandwidth. For example, a medium range of 1-10 km only results in 10 kHz of bandwidth, whereas short range of 0.1-1 km can achieve bandwidth of 20-50 kHz (Akyildiz *et al.*, 2005).

iv. *Limited Energy:* Nodes in UW-ASN are battery powered and charging batteries is hectic. Hence, energy is limited as compared to the terrestrial networks that can even be charged with solar power.

v. *Node Failure:* Last but not least, UW-ASN are prone to fouling and corrosion.

1.3 Problem Background

Stringent underwater environment imposes constraints on human involvement in the exploration of underwater resources. For systematic observations, smooth communication and to obtain optimal results underwater sensor nodes must be able to self-configure, share their coordinates, interactively communicate with other sensor nodes and efficiently pass data to the sink nodes on the surface. However, the downside of traditional exploration mechanism is that they require human involvement that is not possible due to the unpredictable nature of the aquatic environment, vastly monitored area and cost involved. Hence, the efficiency and applicability of traditional mechanisms is limited with some imposed constraints (Prathap *et al.*, 2012). Last but not least, with no inter nodes or offshore communication, traditional mechanisms are not scalable. Hence, they are unsuitable and unreliable for broad coverage. Therefore, the need of an unmanned solution such as routing protocols for efficient monitoring and data collection for large-scale real-time applications are required. A solution where, nodes not only be able to communicate with each other efficiently using acoustic wireless links but also able to relay data and communicate with an offshore control system. Issues in designing a routing protocols are discussed below.

Maturity in terrestrial wireless sensor network technology inspires researchers to experiment using UW-ASN technology in the inhospitable underwater environment. However, UW-ASN poses significant challenges and requires extensive research to obtain resilient, robust network with improved performance. Communication in UW-ASN is not as simple as in TWSN, where common issues like power, energy efficiency, and deployment become significant in 3D underwater topology and must be taken into consideration while designing a routing protocol. Underwater network protocols have high propagation delay in an acoustic medium. This means that the communication overhead must be bound by a minimum threshold to enhance network lifetime concerning energy and to avoid further delay in the slower acoustic medium.

Nodes in underwater networks are equipped with limited battery power and hence utilizing this energy efficiently is one of the most important issues in these networks. Energy efficiency in routing protocols is referred to as providing routing services by reducing energy consumption in events such as transmission/reception of messages, reducing interference, reducing error rate and number of retransmissions attempts (Mundada *et al.*, 2012; Zaman, 2012; Pour, 2015). For example, protocols proposed by Ayaz *et al.* (2012a); Coutinho *et al.* (2013); Wahid *et al.* (2014a, 2015) consume excessive energy in information distribution phase to setup path for data delivery. These protocols flood unnecessary traffic which is not required for setting up data path or never used for data communication. H^2-DAB protocol maintains duplicate paths which it never uses throughout its working process. On the other hand routing protocol such as R-ERP^{2}R by Wahid *et al.* (2014a) deploy uncontrolled flooding, where every new information received at a node such as distance is propagated throughout the network. Hence these protocols consume alot of energy in information distribution phase and are not energy efficient. Moreover, these protocols do not deploy any collision avoidance mechanism and hence collisions are inevitable. Therefore, a controlled flooding technique is necessary in the information distribution phase to reduce high energy consumption. Otherwise, it is possible that a node may die early due to excessive energy consumption and during data forwarding process a source node may not find any data forwarding candidate at next hop.

Another issue of concern is reducing high end-to-end delay in the route planning and data forwarding phase. R-ERP^{2}R considers link quality with energy to form a composite metric for cost calculation for the link at next hop. Composite metric means combining two or more related metrics and estimating link cost based on the combination of these metrics. Routing protocols depend upon estimation of link quality to overcome low power unreliable links and to increase network efficiency in terms of end-to-end delay and node energy (Gnawali *et al.*, 2009; Baccour *et al.*, 2012). In R-ERP^{2}R, link quality is used with energy for node selection at next hop. However, these two metrics are not related, as increase or decrease in energy of the node does not affect the quality of the communication link and vice versa. R-ERP^{2}R does not guarantee selection of nodes with higher energy and or with highest link quality. In first case where R-ERP^{2}R does not select node with highest energy results in reduced network lifetime. While in the second case of link quality, R-ERP^{2}R suffers from packet loss as ETX accounts for partial link quality and suffers with higher end-to-end delay. This is because packet receive ratio for two different nodes at the same distance from the source can be different and less as compared to a node having more distance than these two nodes (Baccour *et al.*, 2012). Moreover, R-ERP^{2}R makes use of DY-NAV 802.11 by Shin & Kim (2008) as MAC layer protocol, which adds to further delay as its a handshaking based protocol. Depth based protocol (DBR), on the other hand, consider a single depth metric for data forwarding and cannot provide a robust path. Its greedy multipath approach results in frequent collisions and require multiple retransmissions to deliver data at next hop. Hence, it also suffers from higher end-to-end delay and higher energy consumption. Moreover, for data forwarding protocol such as H^2-DAB by Ayaz *et al.* (2012a) utilize a reactive multipath approach, which not only add the delay at each next hop but results in collisions as well, especially in dense deployment.

Studies (Liu *et al.*, 2009; Draves *et al.*, 2004) have shown that reliability based metrics such as ETX exhibit better performance than protocols with conventional metrics such as hop count and latency. This is because protocols that use shortest path or minimum hop based metrics rely on the assumption that underlying link is of good quality and hence suffer from performance degradation. In underwater networks the channels are highly unreliable due to the factors described in 1.2.3 and continuous mobility of the node. The continuous node mobility does not allow reliable data connections as in TWSN, where transmission control protocol (TCP) is used to maintain a end-to-end connection. Therefore, routing protocols proposed for underwater networks prefer hop-by-hop communication. In beacon based protocols, R-ERP^{2}R by Wahid *et al.* (2014a) is the only protocol that consider ETX metric proposed by De Couto *et al.* (2005) for estimating the quality of the link. However, ETX accounts for only partial quality of the link which its overestimates (Baccour *et al.*, 2012). Therefore, to resist transient fluctuations in underwater networks, to provide quality of service and to select a stable link between nodes in communication require accurate estimation of the underlying link. The selection of node based on the link quality estimation guarantees reliability, it reduces end-to-end delay by reducing retransmission attempts and by avoiding route re-selection due to link failure (Vigita & Julie, 2013; Baccour *et al.*, 2012). However, link quality is to be used with some related metric for the node selection at next hop.

In the data forwarding phase, it is also noticed that some protocols such as H^2-DAB (Ayaz & Abdullah, 2009) and DBR (Yan *et al.*, 2008) do not provide any scheme to use next hop nodes alternatively and hence compromise the network lifetime. They do not provide any scheme to balance energy or alternative selection of nodes at next hop, rather they repeatedly use the same nodes. As a result, some nodes in the network die early, creating communication voids. A communication void is a situation where a node is unable to find next hop node in the direction of the sink node (Kheirabadi & Mohamad, 2013). Communication voids not only results in unanticipated changes in the topology but also produce signaling overhead in data transmission as data carrying node search for different new paths. Furthermore, in H^2-DAB protocol developed by

Ayaz & Abdullah (2009), the addressing scheme is designed to achieve the high data delivery rate. However, the addressing design is compromising the life of the network by using the same path over and over again. R-ERP^{2}R work on proactive routing tables, which means that once the routing table is built it is only updated after a specific time interval. As a result same nodes are used repeatedly in one interval and hence lifetime of network is reduced. Therefore, a scheme is required using which a node energy status can be updated on regular basis instead of set intervals. This allows a source to choose different nodes in a specific interval and enhance network lifetime.

1.4 Problem Statement

This research is to address the problem of high energy consumption in the information distribution phase due to uncontrolled flooding or unnecessary traffic flow in building up routes. In underwater networks multiple channel impairments together with node mobility result in unstable links. Selection of such links for data communication based on improper quality estimation results in multiple re-transmission attempts that lead to higher end-to-end delay. Therefore, sending data over communication links, requires proper quality estimation of the link between the two neighboring nodes. This research therefore, mainly focuses on next hop neighbor selection based on composite metric (link quality and distance) in data forwarding phase to reduce end-to-end delay. This research also address the issue of inefficient energy balancing schemes that allow repeated use of same nodes for data communication. Such schemes leads to the death of nodes due to frequent usage and reduce lifetime of the network. Therefore, the problem on how to efficiently provide energy balancing has been taken into consideration to enhance the lifetime of a underwater network.

1.5 Research Questions

i. How to control the unnecessary packet flooding to reduce the energy consumption in the information distribution phase?

ii. How to estimate optimal link quality estimation and consider more than one metric to improve end-to-end delay?

iii. How to retrieve and update energy status of nodes at next hop to improve network lifetime in data forwarding phase?

1.6 Aim of the Research

The aim of this research work is to design and develop routing schemes for underwater networks that will enhance information distribution for setting up network path, find an optimized route on hop-by-hop basis and keep communicating nodes informed of their energy status at all times. These schemes work together as one unit and will reduce energy consumption, end-to-end delay in the network while increasing packet delivery ratio and improving the network lifetime.

1.7 Research Objectives

The following objectives are defined to design and develop enhanced hop-by-hop routing protocol in UW-ASN.

i. To design and develop a scheme that controls flooding of hello packet to reduce energy consumption in the information distribution phase.
ii. To design and develop a scheme that estimates link quality and compute cost using a composite metric for the selection of node at next hop to reduce end-to-end delay.
iii. To design and develop an energy balancing scheme that allow energy status update at each communicating node on regular basis to improve network lifetime in data forwarding phase.

1.8 Scope of the Research Work

Many routing protocols for UW-ASN have been proposed in last few years. However most of them assume special setups or requirements. For example either they require a particular sensor (depth calculation sensor) as hardware or require full dimension location or other special equipment for data forwarding. Example of some such protocols that use extra mechanical devices, pressure sensors or localization assumptions includes DFR (Shin *et al.*, 2012), DCR (Coutinho *et al.*, 2013) and DBR (Yan *et al.*, 2008). On the other hand beacon based protocols such as H^2-DAB (Ayaz & Abdullah, 2009), R-ERP^{2}R (Wahid *et al.*, 2014a) do not use any special setups or localization assumptions. Therefore, the scope for this work covers the following points:

i. Nodes movement is not considered continuous, rather node will move up to certain point and come back to its original position.
ii. At MAC layer underwater broadcast MAC is considered for the development of this protocol in random and grid topology.

1.9 Thesis Organization

This rest of the thesis is arranged as follows:

Chapter 2 provides background to the domain and further provides discussion on related issues in underwater networks. Classification of the existing beacon based underwater routing protocols and debate on their strength and weaknesses is provided. Detail on operational working comparison of different protocols for underwater networks are also presented. Finally Chapter 2 discusses research gap used to design and develop beacon based hop-by-hop routing protocol.

Chapter 3 presents detail methodology and discusses the design of the distance based reliable and energy efficient hop-by-hop routing protocol. It provides details on problems of the benchmark routing protocols and presents solution to these problems. Chapter 3 clearly explain objectives of with methodology plan. It provides details on simulation framework, channel model, node energy model and parameters used in the simulation of proposed protocol.

Chapter 4 offers a detail insight development of designed distance based reliable and energy efficient hop-by-hop routing protocol. Information distribution, data forwarding and energy balancing schemes are presented and explained in detail using examples. Moreover, flowcharts of the schemes are also presented that explain the behavior of proposed routing protocol.

Chapter 5 yields performance simulation evaluation of the designed routing protocol. Different performance metrics such as node mobility and packet rate are considered and results are discussed. Moreover, a comparison with benchmark routing protocols based on the packet delivery ratio, energy consumption in information distribution phase, energy consumption in data forwarding phase, end-to-end delay and network lifetime is also presented and explained with the help of figures.

Chapter 6 concludes the work by summarizing the main contributions and findings of the study with some possible future directions.

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