ENHANCED RELIABLE AND ENERGY EFFICIENT PRESSURE BASED DATA FORWARDING SCHEMES FOR UNDERWATER WIRELESS SENSOR NETWORKS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

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SEPTEMBER 2020

DEDICATION

This thesis is dedicated to my parents, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my wife and my family, who supported me through the toughest times.

ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, **Prof. Dr. Abdul Hanan Bin Abdullah**, for encouragement, critics and guidance towards achieving this research. I am also very thankful to my co-supervisor **Assoc. Prof. Dr. Mohd Murtadha bin Mohamad** for his guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM) for partially funding my Ph.D. study. I pay my gratitude to my lab mates, mentors and friends who always supported me throughout my journey, especially Prof. Dr. Muhammad Shafie Bin Abd Latiff, Dr. Ahmed Aliyu, Dr. Zahid Abbas, Dr. Moeen-ud-din Tariq, Dr. Saqib Muneer, Dr. Jameel Ahmed, Dr. Khalid Usmani and Dr. Nisar Ahmed Shakoor.

My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my friends and family members.

ABSTRACT

Data collection in Underwater Wireless Sensor Networks (UWSN) requires highly optimized communication approach in order to achieve efficient data packet delivery. This approach consists of different communication layers of which routing protocol is an important consideration. Several issues including packet entrapment due to void region, selection of forwarding node with insufficient link quality and packet collision in congested forwarding area have emanated. Therefore, three different research problems were formulated to address the issue of reliability and energy efficiency in data forwarding in UWSN. First, void handling for packet entrapment in the void region, which generate delays and communication overhead. Second, non-optimal node selection that causes forwarding delays and non-reliable packet delivery. Third, collision due to congestion, which leads to packet drop and unreliable packet delivery. Thus, enhanced reliable and energy-efficient pressure-based data forwarding schemes for UWSN were developed, which are the Communication Void Avoidance (CVA) to estimate neighbour nodes availability outside a void region in order to avoid voids and reduce delay; a Multi-metric Evaluation mechanism for next forwarder Node Selection (MENS) for optimal packet delivery; and a Congestion Avoidance and MITigation (CAMIT) in data forwarding for congestion and collision reduction in order to achieve reliable data forwarding. Several experiments were performed through simulations to access the performance of the proposed mechanisms and the results of each scheme were compared with related previously published protocols. The obtained results depict that the proposed schemes outperformed the existing schemes and significantly improved overall performance. CVA improved Packet Delivery Ratio by 12.8% to 18.7% and reduced End-to-end delay by 7.3% to 12.5% on average. MENS improved communication Data Rate by 13.2% to 15.1% and Energy Consumption improved by 10.6% to 15.3% on average. Lastly, CAMIT reduced Packet Drop ratio by 10.2% to 13% on average. The findings demonstrate the improved efficiency has been achieved by the CVA, MENS and CAMIT in terms of optimal node selection and reliability in packet forwarding in UWSN.

ABSTRAK

Pengumpulan data dalam Rangkaian Sensor Tanpa Wayar Bawah Air (UWSN) memerlukan pendekatan komunikasi yang sangat optimum untuk mencapai penghantaran paket data yang cekap. Pendekatan ini terdiri daripada lapisan komunikasi yang berbeza di mana penghalaan adalah protokol yang penting. Beberapa masalah termasuk pemerangkapan paket disebabkan oleh kawasan lompang, pemilihan nod pemajuan dengan kualiti pautan yang tidak mencukupi dan perlanggaran paket di kawasan pemajuan sesak telah ditemui. Oleh itu, tiga masalah penyelidikan yang berbeza dirumuskan untuk mengatasi masalah kebolehpercayaan dan kecekapan tenaga dalam pemajuan data di UWSN. Pertama, pengendalian lompang untuk pemerangkapan paket di kawasan lompang, yang menimbulkan lengah dan *overhed* komunikasi. Kedua, pemilihan nod yang tidak optimum yang menyebabkan lengah pemajuan dan penghantaran paket yang tidak boleh dipercayai. Ketiga, perlanggaran akibat kesesakan, yang menyebabkan penurunan paket dan penghantaran paket yang tidak boleh dipercayai. Oleh itu, skema pemajuan data berasaskan tekanan yang boleh percayai dan cekap tenaga untuk UWSN telah dibangunkan yang merupakan Penghindaran Lompang Komunikasi (CVA) untuk menganggarkan ketersediaan nod tetangga di luar kawasan lompang untuk mengelakkan lompang dan mengurangkan lengah; mekanisme Penilaian Multi-metrik untuk Pemilihan Nod Pemacu seterusnya (MENS) untuk penghantaran paket yang optimum; dan Penghindaran Kesalahan dan MITigasi (CAMIT) dalam penghantaran data untuk kesesakan dan pengurangan perlanggaran untuk mencapai pemajuan data yang boleh dipercayai. Untuk menilai prestasi mekanisma yang dicadangkan, beberapa eksperimen dilakukan melalui simulasi. Hasil setiap skema dibandingkan dengan protokol yang dihasilkan sebelumnya. Hasil yang diperoleh menggambarkan bahawa skema yang dicadangkan mengatasi skema sedia ada dan meningkatkan prestasi keseluruhan secara signifikan. CVA meningkatkan Nisbah Penghantaran Paket sebanyak 12.8% hingga 18.7% dan mengurangkan Kelewatan Akhir ke Akhir sebanyak 7.3% hingga 12.5% secara purata. MENS meningkatkan Kadar Data Komunikasi sebanyak 13.2% hingga 15.1% dan Penggunaan Tenaga meningkat secara purata sebanyak 10.6% hingga 15.3%. Akhirnya, CAMIT mengurangkan Nisbah Kehilangan Paket sebanyak 10.2% hingga 13% secara purata. Hasil kajian menunjukkan peningkatan kecekapan telah dihasilkan oleh CVA, MENS dan CAMIT dari segi pemilihan nod yang optimum dan kebolehpercayaan dalam penghantaran paket di UWSN.

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2H-ACK	-	Two Hop Acknowledgement
AEERP	-	AUV aided Energy Efficient Routing Protocol
APCR	-	Adaptive Power Control Routing
ARQ	-	Automatic Repeat Request
AURP	-	AUV-aided underwater routing protocol
AUV	-	Autonomous underwater vehicle
AUV	-	Autonomous Underwater Vehicle
BER	-	Bit Error Rate
CAMIT	-	Congestion Avoidance and MITigation
CCLB	-	Congestion Clustering with load balancing
CNN	-	Convolutional Neural Network
COR	-	Congestion Occurring Region
CVA	-	Communication Void Avoidance
DARP	-	Depth Adaptive Routing Protocol
DBR	-	Depth Based Routing
DFR	-	Depth Forwarding Routing
DREE	-	Distance based Reliable and Energy Efficient
E2ED	-	End to end delay
EC	-	Energy Consumption
E-CARP	-	Energy Efficient Channel Aware Routing Protocol
EEDBR	-	Energy Efficient Depth Based Routing
ERP	-	Environment-aware Routing Protocol
ETX	-	Expected Transmission Count
FBR	-	Focused Beam Routing
FLQE	-	Fuzzy Link based Quality Estimator
GEDAR	-	Geographic and opportunistic routing protocol with Depth Adjustment
GW	-	GateWay
HH-VBF	-	Hop-by-hop Vector-Based forwarding
HM	-	Hello Message

IDC	-	Packet ID
IMU	-	Inertial Moment Unit
IMU	-	Inertial Moment Unit
LARP	-	Location Aware Routing Protocol
LETR	-	Location Error–resilient Transmission Range adjustment–based protocol
LOARP	-	Low Overhead Reactive Routing Protocol
LQI	-	Link Quality Indicator
MENS	-	Multi-metric Evaluation for Next forwarding node Selection
MI	-	Mobility Information
MMS-LETR	-	Modified MSLETR
MPNC	-	Multi-Path Network Coding
MSGER	-	Mobile Sink-based GEographic and opportunistic Routing
MSLETR	-	Mobile Sink-based LETR
NS-2	-	Network Simulator Version 2
NT	-	Neighbour Table
PD	-	Packet Drop ratio
PDR	-	Packet Delivery Ratio
PER	-	Packet Error Ratio
PRR	-	Packet Receive Ratio
PSBR	-	Pressure Sensor Based Routing
QE	-	Quality Estimation
QECT	-	Quality Estimation (Current)
QEU	-	Quality Estimation (Update)
RA	-	Reference Angle
RDBF	-	Relative Distance Based Forwarding Protocol
REBAR	-	Reliable and Energy Balanced Routing Algorithm
RE-PBR	-	Reliable Energy-Pressure Based Routing
R-ERP2R	-	Reliable and Energy efficient Routing Protocol using Physical distance and Residual energy
RSS	-	Received Signal Strength
RSST	-	RSS Threshold

SNR	-	Signal to Noise Ratio
TM	-	Triangular Metric
TOA	-	Time of Arrival
TORA	-	Totally opportunistic routing algorithm
TWSN	-	Terrestrial Wireless sensor networks
TWSN	-	Terrestrial Wireless Sensor Networks
UHRP	-	Underwater Hybrid Routing Protocol
UWSN	-	Underwater Wireless Sensor Networks
VAPR	-	Void Aware Pressure Routing
VBF	-	Vector based forwarding

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter provides a brief background and introduction of the research problems and objectives. The chapter is further divided into 9 sections. Section 1.2 highlights the problem background, importance, and motivation behind this research. This section describes research problem in detail. Section 1.3 shapes problem statement. Section 1.4 states the research questions based on the research problem. The research aim is provided in Section 1.5 while Section 1.6 states research objectives for each of the research questions. Research contribution, significance and scope are presented in Section 1.7, Section 1.8 and Section 1.9 respectively. Finally, Section 1.10 states the organization of this thesis.

1.2 Problem Background and Motivation

Underwater communication was first explored in the World War II when American war ships used to communicate to the control station on island (Ayaz *et al.*, 2011). Insufficient technology equipment is a major hurdle in communication performance. After communication technologies thrive, researchers explored the underwater communication domain. Several communication strategies and architectures have been explored, specifically for underwater due to the unique nature of water as a wireless communication channel. Consequently, routing algorithms for Underwater Wireless Sensor Networks (UWSN) are required for a successful communication. Thus, several research works have proposed different routing algorithms considering the underwater communication challenges. Figure 1.1 represents the full components and elements of the underwater communication setup.

The aim of UWSN routing protocol is to forward the data packet to traverse the best possible path from the source (sender, which is submerged into the water) to the sink (receiver, which resides on the surface of water). The forwarding concept relies on the routing and deployment scheme. In the UWSN, there can be more than one sources and sinks in the same scenario. Afterwards the sink node communicates to onshore access point where all data collection is carried out. The general pattern of communication in UWSN is related to Terrestrial Wireless Sensor Networks (TWSN). However, in the scenario of UWSN, there are several distinctive hurdles including water as communication medium, depth as third dimension, harsh water environment and limited battery capacity. These hurdles directly or indirectly affect the bandwidth and communication issues which lead to communication delay or even data loss. In addition, the movement of the sensors in the underwater due to water current also made the TWSN routing algorithms impractical for UWSN.

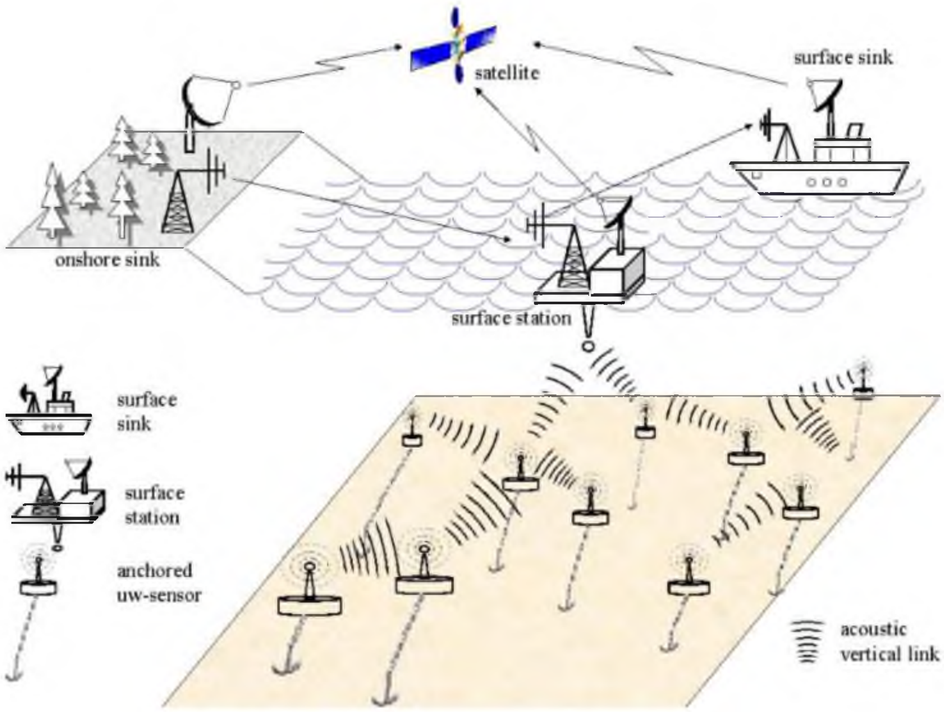

Figure 1.1 Underwater communication in 3D deployment architecture (Pompili *et al.*, 2009)

Water covers the major part of the earth surface area; roughly, 70% of the whole planet area is covered by water. Several research works have stated that only 10% of water area is discovered, while the rest of the water area is yet to be explored

(Khan *et al.*, 2018). The mysterious underwater world fantasizes researchers from all fields of research. The investigations have led to important information collection such as disaster prediction, weather forecast, resources exploration, and tactical surveillance. Oceanic data collection plays an important role in the exploration of the underwater. Thus, the data collection concept requires a good communication model that is, routing algorithm is as important as the network itself. Hence, the routing algorithm plays a vital role in communication. There exist several routing protocols, which have been proposed in different research works in order to achieve better data communication in underwater. However, unlike TWSN routing protocols, UWSN routing protocols are not fully matured thus, requires further exploration to fill in the research gaps.

In UWSN, there are two fundamental issues in the course of data forwarding, reliability driven data forwarding and energy efficient data forwarding. The underwater nodes are faced with the aforementioned issues. In terms of the reliability issues, there is no guarantee of data delivery during packet forwarding due to various factors including node displacement, node's residual energy and congestion. Major cause of node displacement is continuous water currents, which leads to the creation of void regions. Considering the energy efficiency issue, underwater nodes are furnished with battery, which is the only source of power available (Wahid and Kim, 2012a; Tariq *et al.*, 2015). In contrast to the TWSN, the energy depletion in relation to transmission and reception in the UWSN is increased because of the acoustic waves, which serve as a communication medium (Han *et al.*, 2015). Therefore, the transmission/ receive of packet depletes higher percentage of the battery power (Khan *et al.*, 2018). Packet routing in the UWSN node is the critical part that has the obligation to forward and receive data packet in the network (Khan *et al.*, 2018). Therefore, to attain energy-efficiency in the routing procedures, some strategies needed to be taken into account. An energy efficient routing scheme must be developed optimally to decrease the energy depletion and select the most reliable and energy efficient node for data forwarding. Water as wireless communication channel has two major features including high propagation delay and highly prone to link error. These features led to the exploration of different solutions in the underwater data forwarding.

One of the prominent data forwarding algorithms is the opportunistic routing concept. The opportunistic routing employs the broadcasting concepts of the wireless medium, which selects a next forwarding node in a hop-by-hop mode. A suitable next forwarding node is determined based on its ability to act as a best forwarding node (Khasawneh *et al.*, 2016). The opportunistic routing uses flooding concept that achieves better packet delivery rate and throughput but depletes more energy (Darehshoorzadeh and Boukerche, 2015). Thus, the opportunistic routing algorithms require an improvement in order to minimize the energy consumption while at the same time improving the packet forwarding delivery rate. Several energy efficient and reliability driven opportunistic routing protocols have been suggested (Ghoreyshi *et al.*, 2017). These suggested studies focus on selecting next forwarding node from the sea depth node to the sink node at the surface of the sea on energy reduction strategy. The strategy is based on obtaining the position information for selecting a suitable next forwarding node. Therefore, the obtainable routing concepts can be generally divided into two parts including position centric and non-position centric. The position centric routing is a strategy whereby the next forwarding node is selected considering geographical position information of nodes from a GPS, which serve as the highest condition including energy depletion and network overhead (Wahid and Kim, 2012a). In these protocols, the nodes deplete its battery power in the course of localization process. In contrast, the non position centric routing concept does not require complete position information in order to select next forwarding node. However, several research problems have also emanated in the forwarding process of the data packet. These problems include void area creation, insufficient link quality and congestion in packet forwarding in the UWSN. Void area creation led to unreliable packet forwarding and packet entrapment, which result in packet loss and high energy depletion in retransmission. The insufficient link quality also leads to selection of unsuitable communication link, which can cause packet error and in return result in high-energy depletion. In addition, the congestion in the packet forwarding area could also lead to packet drop that signifies unreliability of packet forwarding, which also causes packet drop and high energy usage.

1.2.1 Void Region Handling in Underwater Wireless Sensor Networks

In the underwater communication, a void is a condition in network where a node does not find any neighbour on its way forward towards the sink (Chen and Varshney, 2007). Inside a void, the node with least depth entraps and then drops the packet due to no further forwarding hop available. This node is called local maxima in a single void region (Noh *et al.*, 2013). The communication void has negative impact on the performance of the routing protocols in the process of packet forwarding specially in a sparse network setting. In UWSN, some studies have attempted to address the communication void problem, by designing algorithms that handles the void area/ node communication (Ghoreyshi *et al.*, 2017).

Therefore, different studies have been proposed in order to handle the communication void issue, such as Void Aware Pressure based Routing (VAPR) (Noh *et al.*, 2013). VAPR presents the integration of the geographical routing concept with the opportunistic routing method was implemented. The VAPR carries out greedy forwarding, based on the depth of nodes. In terms of Depth Based Routing (DBR) protocol it uses depth knowledge (Yan et al., 2008). In DBR, each node broadcasts data packets that are beyond the transmission range to its nodes. Only lower nodes of depth are eligible for packet forwarding while the higher nodes of depth discard the packets. In addition, holding time is estimated to determine the priority for selecting a next forwarding node, so a node with the smaller holding time is considered to be the next forwarding node with the best qualification. In addition, periodic beaconing is used to establish full paths to the sink node, which helps to discover the void area. However, in VAPR, when there is a void space, a forwarding node generates path by either using higher depth nodes or lower depth nodes. Consequently, all nodes having the same forwarding direction (downward or upward) are registered as a forwarding set. However, the frequent beaconing for collecting nodes' information leads to high communication overhead, which in turn causes high consumption of energy.

Another solution for addressing communication void named Geographic and Opportunistic Routing Protocol with Depth Adjustment (GEDAR) has been proposed by Coutinho *et al.* (2016). The solution uses both opportunistic and geographic routing based on depth topology adjustment for void area packet recovery. GEDAR selects a number of candidates for the next forwarding node in the forwarding of data packets into the sink node path. The location details both of the sensor nodes and the sink node are used in the process of forwarding the data packet. Every node within the area of signal coverage is allocated with priority based on the use of the likelihood of packet transmission and advancement. Therefore, the GEDAR evades multiple transmissions and thus only the node with the highest priority is selected for data packet transmission. Meanwhile, in the case where other nodes overhear the transmission request, the nodes with lower priority suppress their transmission. In the case, if there exist no node with the transmission coverage of forwarder node, then there is a displacement to a new position using depth adjustment process. The void node navigates down to the direction of the predecessor node, despite the depth adjustment process. In a case where the predecessor node is not a void node, then the displaced node must forward its data through the predecessor node or else its depth will also be changed. Based on GEDAR strategy, a node always shifts to the bottom to forward its data via predecessor node. It is not clear, in the case of more than one predecessor nodes, how a node will determine its ultimate destination, which will forward the data packet. Active depth adjustment itself is a process with a high energy consumption and slow speed. This technique could therefore lead to longer delays and even to a longer end to end delays and even higher energy consumption in few cases.

The position adjustment considering location error-resilient based on geographical and opportunistic routing technique for void area avoidance in UWSN is presented by Shah et al. (2018). The routing protocol involves four different strategies including Location Error-resilient Transmission Range (LETR) adjustment-based strategy which uses transmission coverage rates for neighbour node assessment. This routing concept addresses the problem when the node fails to discover any candidate node which is within the maximum coverage area defined by the nodes. The LETR also achieves recovery from the communication void area by using the concept of depth adjustment. Further, Mobile Sink-based GEographic and opportunistic Routing (MSGER) and Mobile Sink-based LETR (MSLETR) have been presented to avoid depth due to transmission coverage adjustment and to overcome communication void area by employing mobile sink nodes. In addition, a Modified MSLETR (MMS-

LETR) is used to address noise attenuation at varying depth. It eradicates retransmissions by using load balancing and transfer over multipaths. The calculation of angle for forwarding direction is used in the neighbour node or candidate next forwarder node collection. A candidate next forwarding node is selected by calculating the angle of the present forwarding node in its transmission coverage with the corresponding all neighbour nodes. However, it is not appropriate to estimate the angle of all adjacent nodes in the transmission coverage area as the distribution may be in 180^O based on depth up direction forwarding. The angle estimation Provides containment of the forwarding area using an angle value based on the direction of the sink which could help to reduce energy consumption. Nevertheless, in a fragmented network's worst-case situation, there could be no node present in the restricted region which may lead to packet drop during contact. Since the main issue is addressing communication void, confining a forwarding area could also exacerbate the issue of void area/ node. It furthermore does not handle the study's dynamic underwater environment. Therefore, a remedy that can deal with both the best case and the worst-case situation of the connectivity vacuum needs to be discussed further. Considering the aforementioned communication void handling solutions, the issue of continuous node movement due to constant water current during next forwarding node selection has not been addressed.

1.2.2 Insufficient Link Quality Estimation in Underwater Wireless Sensor Network

In UWSN packet forwarding is done hop by hop and during this process one of the available nodes is selected for packet forwarding. There are several parameters in underwater communication, of which only a handful have impact on the performance of the communication between two nodes. In the existing literature, few studies addressed the problem of selecting the best next forwarder nodes based on some critical metrics considering communication link quality (Wahid and Kim, 2012a; Khasawneh *et al.*, 2018). In addition, the use of non-optimal collection of forwarding nodes has a direct or indirect effect on the efficiency of packet forwarding and on the energy depletion of the sensor node. Some critical multiple metrics have not been taken into account for most of the current data packet forwarding in UWSN solutions, as mentioned by Khasawneh et al. (2018). The lack of consideration of the essential multiple metrics leads to packet drop and packet re-transmission, leading respectively to unreliability in packet forwarding and high energy depletion. The use of several metrics for efficiency of the links has a significant effect on increasing the stability of the packet forwarding and energy depletion of the sensor nodes. By contrast, the use of poor multi-metric link quality in the packet forwarding process could result in lower packet delivery and retransmission, leading to unreliability in packet forwarding and high energy depletion (Wahid, Lee and Kim, 2014). For example in (Yan *et al.*, 2008), the study focus on position free routing strategy dubbed Depth Based Routing (DBR). The DBR uses the depth knowledge of each node as a common criterion for choosing the right underwater forwarder node. A present forwarding node estimates the depth level and transmits the data packet with the depth information. Every neighbour node collects the packets of data and determines the depth of the other neighbour nodes. The adjacent nodes then equate their respective depth with the corresponding depth information contained in the packet of data. The nodes with a lower depth than the present forwarder node are therefore deemed to engage in the forwarding process. However, each node has a distinctive holding time for carrying packets of data. The node with the lowest depth is the node with the shortest holding time. Consequently, the node with the shortest holding time is employed for the forwarding process. However, based on these aforementioned strategies, the battery power of the nodes with the lower holding time will depletes more quickly. Therefore, there will be imbalance in the energy depletion of nodes and overall reliability in data forwarding.

Furthermore, a position-free concept based on physical distance, which is dubbed as Reliable and Energy efficient Routing Protocol using Physical distance and Residual energy (R-ERP^{2}R) has been proposed by Wahid et al. (2014). The protocol focuses on enhancing the reliability among nodes by choosing the next forwarder nodes considering link quality. Therefore, it employs a link reliability metric called Expected Transmission Count (ETX) proposed by Couto et al. (2005) alongside physical distance and residual energy level. R-ERP^{2}R involves three stages including initialization, forwarding and cost updating with maintenance stage. The activation stage involves exchanging the residual energy with the adjacent node and then calculating the physical distance with ETX. Additionally, each node transmits the information generated to accessible neighbours. Each node stores information about its neighbours regarding ETX, residual energy, and physical distance. In the data forwarding point, present forwarder chooses the next forwarder nodes, which are closest to the sink node with higher residual energy and maximum rate of communication. In the third stage, which is the final stage, the distance between nodes is re-estimated after a specified interval by broadcasting hello message. However, the frequency of next hop count might increase in the case of dense networks, which result in more energy depletion. Instead of hop based distance, R-ERP^{2}R considers distance between node and sink in a straight line, which can vary in real world scenario. Thus, physical distance as a part of multi metric, might decrease data forwarding reliability and increase overall energy consumption.

Considering the mentioned issues in the limitation of ETX, a Reliable Energy-Pressure Based Routing (RE-PBR) has been suggested (Khasawneh *et al.*, 2018). The UWSN RE-PBR protocol is also based on the concept of position free. The protocol takes into account three parameters including residual energy, depth level and quality of connections, which are used to balance energy and increase reliability in data packet forwarding. Precisely, the efficiency of the link is based on a Triangle Metric (TM) method involving several metrics like the Link Quality Indicator (LQI) and the Signal to Noise Ratio (SNR) method. TM requires fewer control packets to change the state, and this is a lightweight way of calculating the consistency of the connections, thereby providing quicker performance. RE-PBR employs TM to calculate the cost of the link, however in the calculation it avoids Packet Receive Rate (PRR) in the calculation. In addition, it uses a fixed threshold timer called CHECK_TIME to periodically update the network status for proactive route maintenance. However, it comes with the challenge of synchronization with nodes movement, which in underwater are freely moveable majorly due to water currents, thus creating route maintenance and incorrect estimation issues.

Above mentioned issues depict the need of multi-metric next node selection scheme which carefully selects the communication quality estimation parameters in an energy efficient manner. In addition, it requires to match the dynamic underwater environment for increasing reliability.

1.2.3 Congestion Forwarding Area in Underwater Wireless Sensor Networks

In the data packet forwarding for UWSN, the communication is basically self-sustainable, which also contain numerous number of sensor nodes that are distributed randomly in the underwater (Dong *et al.*, 2016). The nodes distribution is non-uniform considering the water current. Thus, the sensor nodes might be concentrated in a certain area that lead to congestion in the communication due to high exchange of control packets (Goyal *et al.*, 2016). Meanwhile, several authors have mentioned that there is need to further explore the congestion issues in the underwater packet forwarding (Ding, 2018; Shah *et al.*, 2018). Traffic congestion happens when the packet traffic is greater than the individual or aggregate capacity of the underlying channel of communication. Consequently, some theoretical work to tackle underwater packet forwarding congestion has been proposed in the three separate cases including tracking, avoidance and recovery. A congestion control mechanism (DCCM) has been proposed in UWSN based on time delay to resolve the problem of imbalances in data packet transmission contributing to congestion (Dong *et al.*, 2016). The congestion control system involves investigating boundless and positive equilibrium, in which the sample density is positive for each node and different flows of events coexist. That means the node sample can't be more than channel's environmental carrying capacity. The delay is regarded as a bifurcation parameter dependent on the time principle, and complex behaviour that involves local stability and Hopf bifurcation is discussed. The research reveals that time delay in transmission provides a crucial advantage, otherwise the device loses its reliability, and a bifurcation of the Hopf occurs. That means the UWSN communication will become congested or even collapsed. Thus, the center manifold theorem and normal form theory are employed for deriving the direction and stability of the bifurcation periodic solution. However, the employment of time delay is not sufficient controlling congestion in the data packet forwarding area. In addition, this solution requires multihop data collection from several neighbours in order to estimate congestion.

Another solution for congestion control scheme has been suggested considering clustering approach with load balancing, which is based on inter and intra clustering concept (Goyal *et al.*, 2016). The clustering scheme is developed to identify congestion within clusters, and among clusters. The detector is for determining the extent of packet collision inside and outside the clusters. In addition, the congestion is minimized by balancing the load of packet traffic between cluster members in the network. Meanwhile a cluster head performs the task of calculating density of a specific cluster in the cluster method, which results in energy loss in the heads of the cluster. It could lead to loss of packets during the packet forwarding cycle because of dead nodes in the network. Considering the aforementioned drawbacks, there is a need to explore an extensive solution in UWSN, which is centered on data packet forwarding reliability and energy efficiency.

1.3 Problem Statement

This research addresses some critical problems that exist in the data forwarding in UWSN, specifically, in packet forwarding transmission. The existing packet forwarding process in the underwater are faced with some issues including communication void, which occur due to dispersed node distribution and irregular water currents. Void region leads to packet loss and retransmission that result in unreliability in packet delivery and energy depletion in the nodes. Further, the selection metrics for next forwarder node in packet transmission are not sufficient for estimating an eligible node. The existing multi-metric mechanisms for estimating the eligibility of next forwarder do not consider the dynamic underwater environment. Additionally, the inefficiency in information collection and distribution phase result in longer convergence time. Thus, it leads to packet error or packet loss. Additionally, in the underwater communication there exist the issue of congestion due to displacement of node by the water current and limited data rate in UWSN communication. Even though, some studies have tried to address the congestion problem however, the solutions are mostly considering a larger number of input parameters or require high computation with long convergence time. Thus, there is need to explore a more robust solution considering the reliability and limited available energy.

1.4 Research Questions

Considering the aforementioned discussions provided in Section 1.2 and 1.3, the following research questions are formulated.

(a) How to discover and handle communication void considering dynamic environment of UWSN?

(b) How to improve multi-metric evaluation for next forwarding node selection based on priority of selection parameters?

(c) How to evade and handle packet traffic congestion considering the aggregated capacity of the underlying communication channel?

1.5 Research Aim

The aim of this research is to design and develop a reliable and energy efficient data packet forwarding scheme for UWSN by adapting pressure-based routing. The scheme aims at avoiding communication void in underwater packet forwarding. Further, it selects suitable and optimal next forwarding node for data packet forwarding based on multi-metric route cost estimation to improve packet delivery and minimize energy. Additionally, the scheme reduces packet drop ratio by considering packet traffic congestion in the data packet forwarding over UWSN.

1.6 Research Objectives

The research objectives are formulated and expressed based on the research questions stated in Section 1.4. The objectives of the research are as follows.

(a) To design and develop Communication Void Avoidance (CVA) scheme based on dynamic movement handling to efficiently detect and handle dynamic void regions.

(b) To design and develop a Multi-metric Evaluation mechanism for next forwarding Node Selection (MENS) scheme based on lightweight optimal link quality selection to achieve low overhead communication in dynamic UWSN.

(c) To design and develop Congestion Avoidance and MITigation (CAMIT) scheme based on congestion probability and congestion mitigation in data forwarding region to lower packet collision and drop rate.

1.7 Research Contributions

Based on the research objectives, the problem of pressure-based routing in UWSN dynamic environment is addressed. First, is communication void handled by Communication Void Avoidance (CVA) mechanism by first detecting and then avoiding the void regions in dynamic underwater environment. It reduces data retransmissions, which in turn improves packet delivery ratio in UWSN. Second, is the Multi-metric Evaluation mechanism for next forwarder Node Selection (MENS) improves communication reliability and network lifetime by implementing lightweight information collection and multi-metric selection procedure. Third, is Congestion Avoidance and MITigation (CAMIT) for minimizing packet collision, which in turn reduce energy depletion in the UWSN.

1.8 Research Scope

In order to achieve the goals of this research, the following limitations are considered as the scope of the research.

(a) All nodes are homogeneous regarding initial energy, energy consumption that is, transmission and receiving per bit, sensing, memory size and communication range.

(b) In the shallow underwater environment, salinity and temperature have an insignificant impact on sound speed. Therefore, the effects of these parameters on sound speed have not been considered in this research.

(c) Security issues regarding sensor node forwarding data packets have not been considered in this research.

(d) All nodes are equipped with a low-cost low power Inertial Moment Unit (IMU) that provides information about node movement

1.9 Significance of the Research

This research study contributes significantly to the field of underwater data collection for the harsh underwater condition using UWSN. The research focuses on energy efficiency and reliability in the underwater wireless communication. Therefore, the proposed reliable and energy-efficient data communication improves underwater data collection. The improved data collection enhances underwater surveillance and monitoring (Ayaz *et al.*, 2011). The monitoring could be on underwater oil pipelines, underwater creatures and underwater border security. With improved and reliable water monitoring, it could lead to saving of loss of millions of dollars (Ayaz *et al.*, 2011).

1.10 Thesis Organization

The remaining part of this thesis is structured as follows.

Chapter 2 provides an extensive and comprehensive literature of the research study area discussing the problem background and present solutions. Chapter 3 describes the methodology adapted in this research and the experimental setup of the environment used to implement and test the objectives. Chapter 4 depicts the design and development of the Communication Void Avoidance (CVA) mechanism. Chapter 5 presents the Multi metric Evaluation mechanism for next forwarder Node Selection (MENS). Chapter 6 provides the discussion of the Congestion Avoidance and MITigation (CAMIT) scheme for collision reduction. Chapter 7 concludes this research work and provides research achievements and suggestions for the future direction of research work.

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