MULTI-LAYER APPROACH FOR ENERGY EFFICIENT OPPORTUNISTIC ROUTING PROTOCOL IN UNDERWATER SENSOR NETWORKS

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"To My Loved Ones"

This is for you

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ABSTRACT

The Underwater Sensor Networks (USN) are known to be an emerging technology due to numerous applications in aqueous environments. The traditional routing protocols used in terrestrial sensor networks could not be applied for underwater due to the various unique characteristics of USN such as unreliable link, inadequate bandwidth, short life span of battery power, high packet drop rate, and attenuation. Therefore, routing protocols are specifically designed to conform to the characteristics of USN. A multi-layer Opportunistic Routing (OR) approach is an example that offers a promising method to overcome those limitations. Research indicated three critical problems in relation to designing USN: selecting the next reliable energy-efficient forwarding nodes, optimal forwarding path, and communication void. Three protocols were proposed to overcome these problems. First, in dealing with improper high energy consumption and candidate nodes selection problem, an Energy-Efficient Opportunistic Routing (EE-OR) protocol is developed aiming to select the next candidate nodes using depth information and energy metrics. Second, the EE-OR protocol is enhanced aiming to manage the unnecessary forwarding suppression problem using a multi-layer OR approach. The Optimal Path Energy-Efficient Routing (OPEE-OR) protocol is designed to reduce the number of transmissions and control path selection. Third, Energy-Efficient Void Avoidance Opportunistic Routing (EEVA-OR) protocol (a modified version of OPEE-OR) is designed aiming to identify void nodes and avoid these nodes during the process of forwarding data packets. Further, in order to evaluate the performance of the respective developed protocols, several simulations were conducted using AquaSim. Findings were compared to Depth Based Routing (DBR), Energy Efficient Depth Based Routing (EEDBR), Reliable and Energy Efficient Pressure-Based Routing (RE- PBR), Enhanced Void Avoidance Routing (E-VAR), and Void Aware Pressure Routing (VAPR). In addition, findings were also compared in terms of network lifetime, total energy consumption, packet delivery ratio, total number of data packets forwarded, and total number of forwarded void detection packet. Finally, findings also indicated that the EE-OR, OPEE-OR and EEVA-OR protocol performed better regarding network lifetime, total energy consumption (6-24%, 19-32%, 17-32%), packet delivery ratio (3-16.6%, 2-14%, 1.5-13%) and the total number of data packet forwarded (4-18%, 18-31%, 5-28%) respectively. In conclusion, the proposed energy efficient void avoidance opportunistic routing protocol tends to improve energy efficiency and packet delivery ratio; and this leads to the expansion of the corpus of knowledge in the area of underwater sensor networks.

ABSTRAK

Rangkaian Sensor Dalam Air (USN) adalah teknologi yang muncul kerana wujud pelbagai aplikasi di dalam lautan. Di dasar laut, protokol penghalaan tradisional yang digunakan dalam rangkaian sensor terestrial tidak dapat diterapkan kerana ciri unik USN. Terdapat beberapa permasalahan berkaitan pembinaan rangkaian sensor dalam air termasuk ketidakstabilan pautan, jalur lebar yang tidak mencukupi, jangka hayat kuasa bateri yang pendek, kadar pengguguran paket yang tinggi, dan pemerosotan yang tinggi. Oleh itu, protokol penghalaan mesti dirancang khusus untuk USN. Penghalaan Oportunistik (OR) berlandaskan kaedah berlapis menawarkan kaedah yang boleh mengatasi kekurangan ini. Kajian menunjukkan bahawa terdapat tiga masalah kritikal dalam membina USN: pemilihan nod cekap tenaga, laluan optimum, dan nod lompang. Tiga protokol dicadangkan untuk mengatasi masalah ini.Pertama, untuk mengatasi masalah penggunaan tenaga yang tinggi dan pemilihan calon nod yang sesuai, protokol Penghalaan Cekap Tenaga Oportunistik (EE-OR) dibangunkan untuk memilih calon nod seterusnya menggunakan maklumat kedalaman nod dan metrik tenaga. Kedua, protokol EE-OR ditingkatkan dengan menggunakan kaedah berlapis untuk menangani masalah penghantaran paket yang tidak diperlukan. Penghalaan Cekap Tenaga Oportunistik Laluan Optimum (OPEE-OR) dibangunkan untuk mengurangkan jumlah penghantaran dan pemilihan jalur kawalan. Ketiga, protokol Penghalaan Cekap Tenaga Oportunistik Penghindaraan Lompang (EEVAOR) adalah (versi OPEE-OR yang diubahsuai) yang direka untuk mengenal pasti nod lompang dan mengelakkan nod ini semasa proses pengiriman semula paket. Selanjutnya, untuk menilai prestasi protokol yang telah dibangunkan, beberapa simulasi dijalankan menngunakan AquaSim. Dapatan akan dibandingkan dengan Penghalaan Berasaskan Kedalaman (DBR), Penghalaan Cekap Tenaga Berasaskan Kedalaman (EEDBR), Penghalaan Cekap Tenaga dan Andal Berasaskan Tekanan (RE-PBR), Penghalaan Penghindaran Lompang Dipertingkatkan (E-VAR), and Penghalaan Tekanan Kesedaran Lompang (VAPR). Sebagai tambahan, hasil dapatan juga dibandingkan dari segi jangka hayat rangkaian, jumlah penggunaan tenaga, nisbah penghantaran paket, jumlah paket data yang kirim semula, dan jumlah paket pengesanan lompang yang dikirim semula. Akhirnya, hasil menunjukkan bahawa protokol EE-OR, OPEE-OR dan EEVA-OR masing-masing menunjukkan prestasi yang lebih baik sepanjang jangka hayat rangkaian, jumlah penggunaan tenaga (6-24%, 19-32%, 17-32%), nisbah penghantaran paket (3-16.6%, 2-14%, 1.5-13%) dan jumlah keseluruhan paket data yang dihantar (4-18%, 18-31%, 5-28%). Kesimpulannya, protokol Penghalaan Cekap Tenaga Oportunistik Penghindaran Lompang yang dicadangkan cenderung untuk meningkatkan kecekapan tenaga dan nisbah penghantaran paket; dan ini membawa kepada pengembangan pengetahuan dalam bidang rangkaian sensor bawah air.

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2H-ACK	-	Hop-By-Hop ACK
3D	-	Three Dimensional
AMCTD	-	Adaptive Mobility of Courier Nodes in Threshold-Optimized DBR Protocol
CDMA	-	Code Division Multiple Access
CMU	-	Communications Management Unit
Co-Im-GEDAR	-	Co-Improved Geographic Depth Adjustment Routing
CSSR	-	Call Setup Success Rate
DBMR	-	Depth-Based Multi-Hop Routing
DBR	-	Depth Based Routing
DFR	-	Directional Flooding-Based Routing
DSR	-	Dynamic Source Routing
DSSS	-	Direct Sequence Spread Spectrum
ECR	-	Energy Consumption Ratio
EDORQ	-	Energy-Efficient Depth-Based Opportunistic Routing with Q-Learning
EEDOR-VA	-	Energy Efficient Depth-based Opportunistic Routing with Void Avoidance
EEDBR	-	Energy-Efficient Depth-Based Routing
EEEDBR	-	Enhanced Energy-Efficient Depth Based Routing
EEF	-	Energy Efficient Fitness-Based Routing
EE-OR	-	Energy Efficient Opportunistic Routing
EEVA-OR	-	Energy Efficient Void Avoidance Opportunistic Routing
EPA	-	Expected Packet Advance
ERP^2R	-	Energy-Efficient Routing Protocol Based on Physical Distance and Residual Energy
E-VAR	-	Enhanced void avoidance routing
FBR	-	Focused Beam Routing Protocol

GEDAR	-	Geographic and Opportunistic Routing with Depth Adjustment Based Topology Control for Communication Recovery
GPS	-	Global Positioning System
H^2-DAB	-	Hop-By-Hop Dynamic Addressing Based
HCREP	-	Hop Count Reply
HCREQ	-	Hop Count Request
HH-VBF	-	Hop-By-Hop Vector-Based Forwarding
ICRP	-	Information Carrying Routing Protocol
Im-GEDAR	-	Improved GEogrphic Depth Adjustment Routing
IVAR	-	An Inherently Void Avoidance Routing Protocol
LASR	-	Location Aware Source Routing Protocol
LCAD	-	Location-based Clustering Algorithm for Data Gathering
LLSR	-	Location-Free Link State Routing
MAC	-	Medium Access Control
NT	-	Neighbour Table
OPEE-OR	-	Optimal Path Energy Efficient Opportunistic Routing
OR	-	Opportunistic Routing
OVAR	-	Opportunistic Void Avoidance Routing
PDR	-	Packet Delivery Ratio
PER	-	Power-Efficient Routing Protocol
QELAR	-	Q-Learning-Based Energy-Efficient and Lifetime-Aware Routing Protocol
RECRP	-	Reliable Energy-Efficient Cross-Layer Routing Protocol
RE-PBR	-	Reliable Energy-Efficient Pressure-Based Routing Protocol
R-EPR^{2}R	-	Reliable Energy-Efficient Routing Protocol Based on PhysicalDistance and Residual Energy
RF	-	Radio Frequency
RREP	-	Route Request Requests
RREQ	-	Route Request Packets
RSSI	-	Received Signal Strength Indication
RPSOR	-	Reliable Path Selection and Opportunistic Routing

SEEORVA	-	Secure and Energy-Efficient Opportunistic Routing Protocol with Void Avoidance
SEANAR	-	Energy-Efficient and Topology-Aware Routing
SUN	-	Source Routing Protocol for Underwater Acoustic Networks
TDoA	-	Time Distinction of Arrival
TCP	-	Transmission Control Protocol
ToA	-	Time of Arrival
TSN	-	Terrestrial Sensor Networks
USN	-	Underwater Sensor Networks
VAEEPR	-	Void Avoidance Energy Efficient Pressure Based Routing
VAPR	-	Void Aware Pressure Routing
VBF	-	Vector Based Forwarding
VBVA	-	Vector-Based Void Avoidance
WDFAD-DBR	-	Weighting Depth and Forwarding Area Division DBR

LIST OF SYMBOLS

$\alpha(f)$	-	Absorption coefficient
μ_i	-	*i-th* Sensor node
$A(l; f)$	-	Signal attenuation
ACK	-	Acknowledgment packet
ADV_f	-	Advancement factor
CN	-	Candidate Node
d	-	Setup for setting the threshold value
d_i	-	Depth variance
depth	-	Depth
EC	-	Energy consumption
ECR_{Ni}	-	Energy Consumption Ratio
ECR_EM	-	Energy metrics
e_d	-	Normalised residual energy
E_{max}	-	Maximum residual energy
E_{min}	-	Minimum residual energy
E_{ackNi}:	-	*EC* cost of the node in broadcasting acknowledgement packet
E_{idleNi}:	-	*EC* cost of the node N_i in idle mode
E_{re_txNi}:	-	*EC* cost of retransmitting a packet to its forwarders using E_{Trans} and $E_{Receive}$
$E_{Receive}$	-	Cost of receiving power
E_{rxNi}:	-	*EC* cost of node *i* to forwarders using receiving power

E_{Trans}	-	Cost of transmission power
E_{txNi}:	-	*EC* cost of node *i* to forwarders using transmission power
$E_{TECNodei}$	-	Total energy consumed by node i.
ECNi	-	Scarceness on residual energy
E_r	-	Residual energy
h	-	Height above the threshold value
hp	-	Hello packet
i	-	Node
id	-	Unique node id
j	-	Arbitrary node
jitter	-	Random number jitter
k	-	Spreading coefficient
k_i^{NF}	-	Next hop forwarder
N	-	Node
N_{dpFi}	-	Number of data packets forwarded by node i
N_{vcTxi}	-	Number of forwarded control packets sent by *i*-th node
N_a	-	Probability of supplementary node
N_p	-	Probability of primary node
ne	-	New record for NT
NFT_i	-	Network finish time
NL	-	Network Lifetime
NST_i	-	Network starting time
NT	-	Neighbour Table
R	-	Radius
re	-	*Residual energy*

RE_{Ni}	-	Residual Energy
$RELi$	-	Reliability index
PR	-	Number of packets received in ith simulation
PS	-	Packets sent in ith simulation
Q	-	Queue
S	-	Source Node
s	-	Length of the arc
S_N	-	Sink Node
S1	-	Primary region
S2	-	Supplementary region
S3	-	Depth threshold
SPi	-	Shortest Path Index
$TEngCons$	-	Total energy consumption
$TnumDPFwd$	-	The total number of data packets forwarded
T_h	-	Holding time
T_{hi}	-	Holding time
$t_{Holding}$	-	Holding time
T_{now}	-	Time
$T_{EngCons}$	-	Total energy consumption
$T_{numDPFwd}$	-	Total number of data packets forwarded
$Timer_{Data}$	-	Timer for received data
t_r^s	-	Transmission range
Z_{sl}	-	Depth of node

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CHAPTER 1

INTRODUCTION

1.1 Overview

Underwater Sensor Networks (USNs) as a platform for aqueous research have gained much attention and a strategy is required for the development of different potential applications. Monitoring the aquatic environment and dynamic changes of the ocean is not an uncomplicated task. This chapter introduces of the problems associated with USN and direction of this research. The second section discusses the motivation for conducting this research. Section 1.3 and Section 1.4 presents the research background and problem statement respectively. Sections 1.5 until Section 1.6 discusses the goals, questions and objectives of the research. Then, Section 1.7 presents the scope of the research. Finally, Section 1.8 covers the thesis organisation.

1.2 Motivation

The surface of the earth consists of seventy one percent water. However, most of the underwater environment remains unexplored due to its vastness and harsh environment. In the last decade, there have been significant interests in monitoring the underwater environments for scientific, commercial exploration and military operations. With the cost of sensors dropping and the development of smart sensors, underwater sensor networks (USN) offer an alternative method to better sense and acquire these data (Gupta *et al*. 2020). Applications that implement USN range from aquaculture monitoring, environmental monitoring, disaster prevention, oil extraction monitoring and tactical surveillance (Haque *et al*., 2020; Daudpota, 2019; Huang *et al*., 2009; Pompili and Akyildiz, 2009; Pompili *et al.,* 2006b).

Terrestrial sensor networks (TSN) have been well investigated and research conducted on the communication protocols have been proposed and reported often. However, the characteristics of USN differs to that of the TSN. In USN, several autonomous and self-organizing sensors nodes are deployed at different depths to collect information and forward them to a destination. A group of sensor nodes are anchored to the bottom of the ocean. Other sensor nodes act as a relay to one or more sinks nodes by means of wireless links. When deployed in an underwater environment, the channels attenuation or loss of signal for electromagnetic waves is 45 times the square root of the frequency decibels per kilometer (Saini *et al*., 2017). Even though optical waves do not suffer from high attenuation, the problems of scattering still affect them (Stojanovic and Preisig, 2009). Therefore, in contrast with terrestrial wireless sensor networks, USN uses acoustic communication, where the attenuation is directly proportional to frequency and distance, and the scattering loss is considerably lower compared to electromagnetic and optical waves (Quazi and Konrad, 1982). The characteristics of acoustic communication leads to challenges in deploying fully functional and operational USNs (Hu and Fei, 2010; Huang *et al.,* 2009). First, the acoustic communication channel is severely impaired, especially due to multipath and fading. Second, acoustic communication operates below 30 kHz, thus the available bandwidth is limited depending on both range and frequency due to absorption. Third, acoustic communication experiences high bit error rate and temporary losses of connectivity. Forth, unlike electromagnetic communication, the propagation delay is five times magnitude higher than radio frequency in TSN. Fifth, an underwater sensor networks require 100 times more power when transmitting data, as compared to the power required when receiving it (Partan *et al*., 2007). Consequently, USN nodes needs to reserve energy consumption to prolong the network lifetime. Lastly, USN must contend with mobile nodes either due to their dynamical capability or due to random motion caused by ocean currents (Pompili and Akyildiz, 2009; Pompili *et al*., 2006a; Kinsler *et al.,* 1999).

Protocols developed for TSN are based on radio signals' characteristics. Therefore, these protocols are deemed unsuitable for implementation in USN. Efforts to overcome the inefficient communication protocol have been made by researchers alike, while considering the characteristics of USNs. Research in this topic focuses on three main areas namely, data-link layer, network layer, and physical layer. In the data link layer, research on two code-division spread-spectrum access techniques were compared by Freitag *et al*. (2001). While Kalofonos *et al*. (2003) combined multi carrier transmission with the direct sequence spread spectrum (DSSS) and code division multiple access (CDMA). As for the network layer, energy efficient routing protocol were proposed by Rahman *et al.* (2017), Rani (2017), Solayappan *et al*. (2017); and Walayat *et al*. (2017). Localization techniques were investigated by Han *et al.* (2012), Wahid and Kim (2012) and Chandrasekhar *et al*. (2006). While Ghoreyshi *et al*. (2016a), Shah *et al*. (2016) and Yu *et al*. (2015) focused on cooperative routing protocols. Research focusing on the physical layer were conducted by Jeon *et al*. (2011), Hovem (2007), Wills *et al.* (2006), and Stojanovic *et al.* (1994). Although several researches have been performed to deal with routing problem in USNs, each one has its own advantage and disadvantages. Hence, USN remains as a delay tolerant network, thus still requiring specialised routing protocols that can achieve the less energy consumption and high packet delivery ratio.

1.3 Research Background

An underwater sensor network consists of many autonomous and individual sensor nodes that perform forwarding, storing and collecting data. The main issues involved is deploying USN are limited bandwidth, high propagation delay, 3D topology, media access control, routing, resource utilization, and power constraints. The routing protocol of USNs design is more difficult and restricted than terrestrial wireless sensor networks. Therefore, the underwater routing protocol should have the ability to build highly reliable and effective communication links for the network in harsh underwater environments (Li *et al.,* 2016). Underwater routing protocols should be scalable to accommodate dynamic topology changes and stability in the network to cope with various emergencies. The routing protocols usually choose the path to transmit data information from the underwater source nodes to the surface destination nodes. Various protocols have been designed to satisfy the different requirements of the acoustic communications such as delay efficiency, bandwidth efficiency, reliability, cost efficiency, delivery ratio. But the major requirement that has been highlighted is energy efficiency. Energy efficiency depends on many metrics which should be considered while designing the protocol.

The main energy source of USN are batteries, and since the placement of the sensors are in harsh underwater conditions, the process becomes challenging and expensive (Solayappan *et al*., 2017; Menon, 2016). Over time, the number of sensor nodes that expire due to energy loss increases, which in turn decreases the USN coverage area. Therefore, prolonging their lifetime is crucial. To increase the underwater sensor networks lifetime, proper energy efficient routing protocol should be designed to minimise energy consumption.

An underwater sensor node consumes more energy when transmitting a packet compared to when it is receiving one (Casari and Zorzi, 2011). In order to reduce the energy consumption, the number of unnecessary transmissions needs to be reduced. Apart from reducing energy consumption, another method of prolonging the lifetime of a sensor node is by applying energy load ranking techniques among sensor nodes (Wahid *et al*., 2011). The amount of energy consumed during transmission should be balanced amongst the nodes from the source towards the destination.

Energy efficient routing protocols developed for terrestrial sensor networks (TSN) (Banerjee and Misra, 2002; Shah and Rabaey, 2002; Chang and Tassiulas, 2000) cannot be applied directly to underwater sensor networks. One possible solution to overcome the problems associated with underwater sensor networks is by implementing appropriate routing protocols adapted to underwater environments. Thus, the design of routing protocols in USNs should consider energy efficiency, consequently improving the network lifetime whilst without sacrificing system performance (Menon, 2016; Wu and Sun, 2015; Wahid and Kim, 2012; Ayaz *et al*., 2011; Yan *et al.,* 2008).

Routing protocols in underwater sensor networks can be classified into different categories mainly energy-based routing, geographical data information routing, opportunistic routing and data-based routing. Energy-based routing protocols considers the energy usage of the sensor nodes to extend the lifetime of the network. An advantage of this protocol is balance energy consumption and prolonging the lifetime of the network. However, implementing energy-based protocols leads to void holes and high packet overhead. As for geographical protocol the geographic information of the sensor nodes to simplify the topology of the network is considered. By implementing this protocol, the network lifetime can be prolonged but at the cost of data delay transmissions. In data-based routing, the data information transmission from the source node to the destination node to guarantee the integrity of the data packets in the whole transmission process is considered. A disadvantage of implementing the data-based routing protocol is higher energy consumption compared to the other routing protocol. Tt is almost impossible to conclude that any particular routing strategy can cost-effectively solve issues associated with underwater applications because each of them has certain strengths and weaknesses and is only applicable to specific situations.

Opportunistic routing (OR) has been proposed as an alternative routing protocol in underwater environments as it is able to handle certain issues associated within USN (Coutinho *et al.*, 2016; Vieira, 2012). By implementing OR a higher data rate can be guaranteed (Menon and Prathap, 2016). Opportunistic Routing (OR) employs the broadcast nature of wireless sensor nodes to increase the number of probable forwarding candidate nodes in the network.Thus, packet delivery is increased while the number of collision decreases. The disadvantage when employing OR are higher end-to-end delay of data packets, network traffic, and energy consumption (Kheirabadi and Mohamad, 2013; Lee *et al.*, 2010; Schaefer, Ingelrest, and Vetterli, 2009; Biswas and Morris, 2005). This is due to the nodes' transmission coordination process. By carefully designing an OR routing protocol addressing the transmission coordination process, these issues can be eliminated or improved.

Opportunistic routing protocol can be classified into two main categories; location based opportunistic routing protocol or location free opportunistic routing protocols. Additionally, location free protocols are further sub-divided into two subcategories: beacon-based routing protocol or pressure-based routing protocols. Opportunistic routing protocols based on location suffer from low data rate and constraint bandwidth. Existing location-based OR protocols (Nicolaou *et al*., 2007; Xie, Cui, and Lao, 2006) experience rapid energy drainage and void communication holes. Energy constraints maybe due to the fact that these protocols are dependent on the position information of the nodes. Since USN nodes lack a Global Positioning System (GPS) system, location nodes increase the complexity of the routing protocol (Ayaz *et al.*, 2011). This in turn also affects the energy consumption. Unlike, location based OR protocol, location free OR protocols are not dependent on position. Instead, for beacon-based protocols, the networktopology information is needed for the forwarding candidate selection process. While pressure-based protocols require only the depth measurement information to identify the forwarding candidate. In terms of energy efficiency, pressure based OR protocols are more promising to be employed in underwater environments. Pressure based routing does not impose extra overhead or high energy consumption for the forward candidate selection. Ahmed *et al.* (2017) stated that the design of a scalable, robust and reliable routing protocol is needed and must be location free. Location free OR requires less energy as it does not have to compute the location of the node each time data is to be transmitted. Therefore, this research adopts the pressure based OR approach when designing an energy efficient routing protocol.

Designing opportunistic routing protocols comprises of two main process candidate set selection and candidate set coordination. The candidate set selection approach is responsible for selecting a subset of the neighbouring nodes to continue forwarding the packet. Ranking metrics is used to determine the suitability of each neighbour as a forwarding candidate. For both location-based and beacon-based routing, parameters obtain from position and topology information are used as the ranking metrics respectively. In pressure-based routing, the ranking metrics are varied. Depth or hop count information is used as ranking metrics to reduce the number of hops and decrease the energy consumption in protocols as proposed by Coutinho, Vieira, and Loureiro (2013) and Yan *et al*. (2008). Routing protocols proposed by Ashrafuddin *et al*. (2013), Bouk *et al.* (2017), and Guangzhong and Zhibin (2010), both depth and residual energy are incorporated as their ranking metric. The protocol developed by Wahid *et al*. (2011), also adopts both residual energy and depth as the ranking metrics to balance the energy consumption in the network. However, the implementation of the ranking algorithm differs between the existing protocols mentioned above even though the metrics used are similar. It can be concluded that the design and implementation of a ranking algorithm depends on the needs of the application itself.

During candidate set coordination, the coordination of the next-hop forwarding packets operations is processed together with a supressing algorithm for low-priority nodes (Wahid and Dongkyun, 2010; Nicolaou *et al*., 2007). This approach is timer based as well as controlled based. Timer based coordination is the preferred method used in current OR USN. By implementing candidate set coordination the average number of transmissions required to deliver a packet is reduced. By coordinating high-priority and low-priority node candidates to forward only when the higher-priority nodes fail to do so, energy consumption becomes lower and unnecessary transmission of redundant packets are avoided. When both candidates set selection and coordination are employed concurrently, OR protocols become simpler and scalable. Furthermore, there are no complex computations for candidate set selection as it adopts the basic transit and receive procedure. A disadvantage of using this combination of OR procedure is an increase in the occurrence of duplicated packets. When there is an increase in duplicated packets, packet collisions rate increases, and unnecessary energy expenditure occur. Instead of a timer-based approach, depth selection, position based, and normalised packet advancement are applied during candidate coordination (Coutinho *et al.,* 2019). Although significant research on OR design in USNs has been explored, there are several directions that still require further exploration. Gaps still exist in developing a ranking algorithm that reduces energy consumption while providing reasonable packet delivery ratio.

Optimum forwarding hop is the second problem that has a direct impact on increasing the number of retransmissions, increasing energy consumption and reducing the network lifetime. Unnecessary forwarding can be defined as the useless transmissions that occur during the forwarding process. Selecting the node that has less depth than sender in transmission range is commonly used for handling the problem of reducing the number of transmissions and the number of nodes that are selected to forward the data packet (Ghoreyshi *et al.*, 2016). The main disadvantage of this approach is that it totally depends on the distance between sender and receiver node without considering different metrics. In location-based routing algorithms, the sending area has been layered and the shortest path is chosen based on location information that is provided by GPS, shapes and link quality (Shin *et al.*, 2012; Chitre *et al.*, 2008; Hwang and Kim, 2008). Moreover, in location-free routing algorithms, selecting the optimal shortest path is one of the main problems due to lack of GPS information to reduce the transmission area. In addition, opportunistic pressure-based routing algorithm suffers from a lack of efficient shortest path selection algorithm, which leads to reducing the network lifetime and the consumption of high amounts of energy (Jouhari *et al.*, 2016; Noh *et al.*, 2013; Wahid *et al.*, 2012; Yan *et al.*, 2008; Nicolaou *et al.*, 2007). Among the existing opportunistic pressure-based routing algorithms, Depth Based Routing (DBR) (Yan *et al.*, 2008) employs poor shortest path algorithm for handling the problem of nodes reduction and constraints, which is not efficient due to the use of depth information only, which leads to consuming high energy for the selected node due to the lowest depth selection. HydroCast (Lee *et al.*, 2010) and Void Aware Pressure Routing (VAPR) (Noh *et al.*, 2013) employ modifying forwarding set reduction algorithm by ranking the neighbour nodes using 2-hop neighbouring based on physical distance within transmission range. However, the main disadvantage of this algorithm is that it used 2-hop neighbour information, whereas finding this information in USNs is costly due to the use of beacon messages that are provided by sinks, which requires high energy consumption. As a result, it is necessary to enhance the path selection algorithm in opportunistic pressure-based routing algorithm without using full location information and partial information which helps in reducing the total number of data packet forwarding, suppressing the unnecessary forwarding and reducing the energy consumption.

Void communication occurs when a forwarding node cannot find any suitable candidate nodes within its path leading towards the destination. These packets may be dropped even though an alternative path exists between the sender and receiver. When an alternate path to the destination cannot be discovered because void notes are present, data packets may drop, thus wasting the network resources mainly the energy and bandwidth. Factors that contribute to the void communication problems include sparse topology, temporary obstacles, and unreliable nodes or links (Basagni *et al*., 2015; Chen and Varshney, 2007). The presence of void area in the routing path can dramatically decrease the performance of the network. High packet loss and wasting resources are the immediate consequence of not including an appropriate void-handling technique in the routing protocol. To improve routing efficiency, different techniques and recovery methods have been proposed to handle the void problem. Void handling techniques are categorised into two main groups: location based, and depth based. In the location-based category, the void node is determined based on the geographical advancement of the neighbouring nodes. In the depth-based category, a node is considered a void node if it cannot find any neighbouring node with thelower depth than itself. In this case, a packet cannot make any upward progress toward the surface. To overcome the void problem, the most promising technique would be to avoid the void node. This technique minimises the possibility of encountering the void area during packet forwarding. There are different approaches to achieve this objective like Energy Efficient Depth-based Opportunistic Routing with Void Avoidance (EEDOR-VA) (Mhemed et al., 2021), Enhanced void avoidance routing (E-VAR) (Nazareth and Chandavarkar, 2019), Opportunistic void avoidance routing (OVAR) (Ghoreyshi *et al*., 2016) and Void Aware Pressure Routing (VAPR) (Noh et al., 2013). However, these routing protocols still imposes communication overhead when exchanging beacons between the nodes. Therefore, in order to obtain the maximum efficiency, the environmental characteristics, intended application, and unique characteristics of the routing protocol should be considered when designing a new void-handling technique or selecting an existing one.

1.4 Problem Statement

The lifetime of an USN is dependent on effectively managing the energy source. Energy consumption of the sensor networks are largely consumed during the transmission phase. Therefore, several opportunistic routing protocols have been proposed to reduce energy consumption while providing satisfactory packet delivery ratio. Energy efficiency in USNs can be managed effectively and implementing ranking method during candidate set selection (Noh *et al.*, 2013; Wahid and Kim, 2012; Yan *et al.*, 2008). Balancing the energy consumption when ranking the nodes in advancement area, results in lower energy consumption and higher packet delivery ratio. In order to reduce the energy consumption and provide the satisfactory packet delivery ratio, it is necessary to design and develop an algorithm that can rank the nodes in advancement area based on energy metrics. However, existing energy efficient OR protocol ignore this fact. By implementing inefficient ranking methods, energy consumption increases and packet delivery ratio decreases.

Chakchouk (2015) and Raina *et al*. (2016) states that existing OR protocols do not implement shortest path algorithm during forwarding data. An advantage of implementing shortest path algorithm is suppression of unnecessary forwarding of data during transmission. Issues associated with unnecessary forwarding of data include high energy consumption, increase in the number of hops and an increase in the total number of data packets forwarded. Existing protocols that do implement shortest path algorithm use location information based on GPS or beacon messages, thus an increase in the amount of energy consumed in order to collect these information (Coutinho *et al.*, 2016; Kheirabadi and Mohamad, 2013). Therefore, there is a need to introduce an optimal shortest path algorithm to suppress unnecessary transmissions in order to reduce the total energy consumption, reduce the number of hops and to decrease the total number of data packets forwarded.

Communication void leads to packet loss and reduces the packet delivery ratio, especially in underwater sensor networks. Several existing opportunistic routing protocols pay attention to communication void in USNs (Javaid et al., 2018; Ghoreyshi et al., 2017b). The existing solutions employ the location information and topology information to handle this issue. However, such protocols are not energy efficient because finding this information in USNs with dynamic topology causes the energy of nodes to be wasted. For these reasons, it is essential to introduce a void avoidance algorithm that can detect the void nodes without the use of location information and topology information and avoid these nodes in packet forwarding process to improve the packet delivery ratio, especially in sparse networks.

1.5 Research Goal

The main goal of this research is to propose a multi-layer approach in energy-efficient opportunistic routing protocol for USNs to deal with the issue of ranking of nodes during candidate set selection, optimising the forward path selection, and communication void while reducing the energy consumption of nodes and maintaining the packet delivery ratio at a satisfactory level.

1.6 Research Questions

The general research question addressed in this study is:

How to reduce the energy consumption and eliminate the void problem in underwater sensor networks; at the same time provide the satisfactory packet delivery ratio by enhancing the opportunistic routing protocol?

In order to answer this question, research questions are provided as follows:

i. How to select the best candidate node to reduce the energy consumption and improve packet delivery ratio?

ii. How to select the route for packet forwarding with the optimal path while reducing the energy consumption of the whole network and eliminate duplicate packet transmission?

iii. How to identify direct and avoid void nodes and indirect void nodes using the appropriate void handling techniques to optimise packet delivery ratio?

1.7 Research Objectives

In order to achieve the research goal, several research objectives have been identified as follows:

i. To extend the lifetime of the USN while providing satisfactory packet delivery ratio by enhancing energy metrics based on node energy consumption ratio and depth to rank candidate set selection.

ii. To extend the lifetime and decrease unnecessary network traffic due to duplicate packet forwarding in sparse USN by adopting a multi-layer approach to configure an optimal shortest path routing protocol based on distance and energy metrics.

iii. To identify void nodes in the packet forwarding process and extending the lifetime of the network in sparse USN while providing satisfactory packet delivery ratio by adopting a multi-layer approach to configure a void avoidance energy efficient routing protocol.

1.8 Research Scope

The following constraints are considered in this research:

i. In the research, acoustic signals intercepted by sea creatures other than the intended recipient, which alter the transmitted acoustic signal, are not considered.

ii. Underwater nodes send private information and data packets to other underwater nodes in a friendly environment without any security issue between nodes.

iii. All underwater nodes are homogeneous in terms of sensing, communication range, initial energy, memory size, and energy consumption in transmission and receiving per bit.

iv. Since the salinity, temperature, and depth have negligible impact on sound speed in the underwater environment, the effects of these parameters on the speed of sound are ignored in this study.

v. The performance of the proposed protocols is evaluated and validated using the AquaSim package, which is an independent component of the underwater sensor network simulator, NS2.

vi. All simulation scenarios are designed in a 3D architecture.

vii. Literature review is limited to research based on location free opportunistic routing protocols between 2008 until 2020 and at least attempted in solving two of the issues associated with USNs (energy efficiency, optimal path, and void avoidance).

1.9 Thesis Organisation

The remaining chapters of this study are arranged as follows. In Chapter 2, a comprehensive literature review related to research goal and objectives is done in order to formulate the research problem. The research methodology, which is conducted in this research, is provided in Chapter 3. Chapter 4 introduces the design and development of the proposed protocols, Energy-Efficient Opportunistic Routing, Optimal Path Energy-Efficient Opportunistic Routing and Energy-Efficient Void Avoidance Opportunistic Routing. The results and discussion of the proposed protocols is discussed in Chapter 5. Finally, Chapter 6 concludes the thesis, expresses the research contributions, and then presents the recommendations for future studies.

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1. Kamaruddin, A., Ngadi, M.A., Harun, H (2019). Energy Efficient Opportunistic Routing Protocol (EE-OR) for Underwater Wireless Sensor Network. Journal of Physics: Conference Series, IOP Publishing. **(Indexed by SCOPUS)**