TOTALLY OPPORTUNISTIC ROUTING ALGORITHM FOR UNDERWATER WIRELESS SENSOR NETWORK

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

This thesis is dedicated to my beloved parents who have raised me to be the person I am today, to my wife who believes in the richness of learning, to the friends who have trusted me and to my teachers who have led me.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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December 2019

Chair : Fazirulhisyam Hashim, PhD
Faculty: Engineering

Underwater wireless sensor network (UWSN) is the enabling technology for a new era of underwater monitoring and actuation applications. Although acoustic communication has been investigated for decades, however, that mainly focuses on the physical layer and its related issues like low bandwidth and considerable propagation delay. Apart from physical layer issues, nodes localization, data aggregation, and forwarding are also intensely constrained due to channel impairment and which needs due consideration. Until now, the scientific community has yet to investigate the principles that will usher the design of networking protocols for UWSN. It is due to the fact that the protocols designed for terrestrial wireless sensor networks cannot be applied for a UWSN since it uses the acoustic channel instead of a radio-frequency-based channel. This dissertation addresses the problem of nodes localization, real-time data delivery, and void node issue in three-dimensional UWSN. This thesis investigates the localization problem in large scale UWSN and proposes a hierarchical localization scheme. The proposed scheme performs its operation in two stages: anchor node localization and ordinary node localization. The former can be localized by utilizing any of the existing schemes, whereas for the later a *Time of Arrival* (ToA) based distributed 3-dimensional Euclidean distance estimation method has proposed.

Opportunistic Routing (OR) is an advanced technique that can improve the data collection process of a wireless network, specifically the acoustic network. This thesis stipulates a general discussion for high-fidelity and energy-efficient data collection in UWSN. In the first part of the thesis, the symbiotic design of opportunistic routing protocols for UWSN is given in detail. In the second part, a new localization scheme for underwater wireless sensor network has been proposed. In the third part, TORA and NA-TORA have been presented, which are energy efficient and opportunistic routing protocols that rely on node position information for data transmission to

ensure packet delivery. In TORA next-hop forwarder is selected on the fly, where the designated next-hop forwarder is selected based on its distance from the sink node. Whereas in NA-TORA, Expected Transmission Count (ETX) and residual energy of a node are considered for data transmission to ensure packet delivery. The suggested data forwarding algorithms are designed to abstain horizontal transmission, to lower end to end delay and improve throughput and energy efficiency. In the fourth and final part, a void detection and avoidance based routing protocol called NA-TORA with VA has been presented.

The unreliable communication environment of UWSN and the existence of a void node in the routing path improves the chances of not receiving data on the designated next-hop forwarder. Avoiding void nodes in the data forwarding route is quite a challenging task in UWSN due to node mobility and three-dimensional localization. In such cases selecting next-hop forwarder on the fly is one of the solutions, which has been adopted by the proposed opportunistic routing protocols. An extended version of NA-TORA called NA-TORA with VA has been proposed to overcome the problem of void nodes in the data forwarding route by utilizing the angle of transmission adjustment and transmission range extension method. Comprehensive and extensive simulations were performed to assess the performance of the proposed schemes for high network traffic load under widely spaced and very dense network scenarios.

Simulation results show that NA-TORA significantly improves the network performance when compared to some relevant existing routing protocols, such as VBF, HH-VBF, and TORA, for energy consumption, average end-to-end delay, and packet delivery ratio. NA-TORA reduces energy consumption by an average of 44% of VBF, 49% of HH-VBF, and 9% of TORA, whereas the average end-to-end delay has been reduced by 80% of VBF, 79% of HH-VBF, and 10% of TORA. Moreover, the packet delivery ratio has been improved by an average of 51% of VBF, 34% of HH-VBF, and 8% of TORA.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ALGORITMA PENGHALA OPORTUNISTIK PENUH UNTUK RANGKAIAN SENSOR WAYARLES BAWAH AIR

Oleh

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December 2019

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Rangkaian Sensor Wayarles Bawah Air (UWSN) merupakan teknologi pemboleh bagi era baru pemantauan bawah air dan aplikasi penggerakan. Walaupun kajian terhadap komunikasi akustik telah dijalankan selama beberapa dekad, kajian-kajian tersebut hanya tertumpu kepada lapisan fizikal serta isu-isu berkaitan seperti jalur lebar yang rendah dan kelewatan penyebaran yang besar. Selain daripada isu berkaitan lapisan fizikal, pengagregatan dan penghantaran data juga bertindak sebagai kekangan akibat gangguan saluran yang memerlukan pertimbangan yang sewajarnya. Sehingga kini, komuniti saintifik masih belum menyiasat prinsip yang akan membawa reka bentuk protokol rangkaian untuk UWSN. Sehingga ke hari ini, para saintis dan komuniti saintifik masih belum menyiasat prinsip yang akan membawa reka bentuk protokol rangkaian untuk UWSN. Hal ini disebabkan oleh rekabentuk rangkaian sensor wayarles darat adalah berbeza dan tidak boleh digunapakai untuk UWSN kerana ia menggunakan saluran akustik dan bukannya saluran berasaskan frekuensi radio. Disertasi ini membahaskan tentang masalah penyetempatan nod, penyampaian data masa sebenar, dan masalah nod kosong dalam UWSN tiga dimensi.

Tesis ini menyiasat masalah lokalisasi dalam skala besar UWSN dan mencadangkan skema penyetempatan hierarki. Skim yang dicadangkan menjalankan operasinya dalam dua peringkat iaitu penyetempatan nod anchor dan penyetempatan nod biasa, di mana penyetempatan nod anchor dapat dilokalisasi dengan menggunakan skema yang sedia ada, manakala kaedah pengiraan jarak Euclidean 3 dimensi berasaskan $Time of Arrival$ (ToA) telah dicadangkan untuk penyetempatan nod biasa. Rangkaian opportunistik (OR) merupakan teknik moden yang dapat meningkatkan proses pengumpulan data rangkaian wayarles, rangkaian akustik secara khusus. Tesis ini membincangkan secara umum mengenai pengumpulan data dan tenaga yang telus

dan cekap di dalam UWSN. Di bahagian pertama tesis, reka bentuk simbiotik protokol penghalaan oportunistik untuk UWSN telah dijelaskan secara terperinci. Di bahagian kedua, skim penyetempatan yang baru bagi rangkaian sensor wayarles bawah air telah diusulkan. Di bahagian ketiga TORA dan NA TORA iaitu protokol penghalaan yang cekap dan oportunis yang bergantung pada maklumat kedudukan nod untuk penghantaran data untuk memastikan penghantaran paket dibincangkan. Dalam TORA penghantar hop yang seterusnya dipilih dengan cepat, di mana penghantar hop yang ditetapkan dipilih berdasarkan jaraknya dari nod sinki, manakala dalam NA-TORA bilangan transmisi yang diharapkan (ETX) dan penggunaan tenaga nod untuk penghantaraan data dipertimbangkan bagi memastikan penghantaran paket. Algoritma penghantaran data yang dicadangkan direka untuk menahan penghantaran mendatar, mengurangkan kelewatan hujung ke hujung serta meningkatkan keupayaan dan tenaga. Dalam bahagian keempat dan terakhir, pengesan ruang kosong dan protokol penghalaan berasaskan pengelakkan yang dikenali sebagai NA-TORA bersama VA telah dibentangkan.

Persekitaran komunikasi UWSN yang kurang meyakinkan meningkatkan kemungkinan untuk tidak menerima data mengenai penghantar hop seterusnya yang ditetapkan. Mengelakkan nod kosong dalam laluan penghantaran data merupakan tugas yang agak mencabar di dalam UWSN disebabkan oleh pergerakan mobility dan penyetempatan tiga dimensi. Dalam kes sedemikian memilih penghantar hop seterusnya dengan pantas adalah penyelesaian yang tepat, yang mana ianya telah digunakan oleh protokol penghalaan oportunistik. Versi lanjutan NA - TORA yang dipanggil NA TORA Bersama VA telah dicadangkan untuk mengatasi masalah nod kekosongan dalam laluan penghantaran data dengan menggunakan sudut pelarasan penghantaran dan kaedah lanjutan jangkauan penghantaran. Simulasi komprehensif dan menyeluruh telah dilakukan untuk menilai prestasi skim yang dicadangkan bagi beban trafik rangkaian yang tinggi di bawah senario rangkaian yang luas dan sangat padat.

Hasil keputusan simulasi menunjukkan bahawa NA-TORA telah berjaya meningkatkan prestasi rangkaian secara mendadak berbanding beberapa protokol penghalaan yang sedia ada seperti VBF, HH-VBF, dan TORA, untuk penggunaan tenaga, purata kelewatan hujung-kehujung dan nisbah penghantaran paket. NA-TORA telah berjaya mengurangkan penggunaan tenaga dengan purata sebanyak 44% daripada VBF, 49% daripada HH-VBF, dan 9% daripada TORA, manakala purata kelewatan hujung-kehujung telah berjaya dikurangkan sebanyak 80% daripada VBF, 79% daripada HH-VBF, dan 10% daripada TORA. Selain itu, nisbah penghantaran paket telah meningkat dengan purata sebanyak 51% daripada VBF, 34% daripada HH-VBF, dan 8% daripada TORA.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

Ack	Acknowledgment
AOA	Angle of Arrival
AUV	Autonomous Underwater Vehicle
CF	Candidate Forwarder
CS	Candidate Set
CSMA	Carrier-Sense Multiple Access
CTS	Clear to Send
CVBF	Cluster Vector Based Forwarding
DBR	Depth Based Routing
D-DBR	Directional Depth Based Routing
DNR	Dive and Rise
DTN	Double Transmission Node
DUCS	Distributed Underwater Clustering Scheme
EM	Electromagnetic
ES-VBF	Energy-Saving Vector Based Forwarding
ETX	Expected Transmission Count
GIB	GPS Intelligent buoys
GPS	Global Positioning System
H2DAB	Hop-to-Hop Dynamic Addressing Based Routing Protocol
HH-VBF	Hop-by-Hop Vector Based Forwarding
NADV	Normalized Advancement
NA-TORA	Normalized Advancement based TORA
OR	Opportunistic Routing
PDF	Propagation Deviation Factor
PDR	Packet Delivery Ratio
PER	Power-Efficient Routing
P-LOC	Probabilistic Localization
RF	Radio Frequency
RSSI	Receiver Signal Strength Index
RTS	Request to Send
SEA	Sensor Equipped Aquatic
SEANAR	Energy-Efficient and Topology-Aware Routing Protocol
STN	Single Transmission Node
TDOA	Time Difference of Arrival
TOA	Time of Arrival
TORA	Totally Opportunistic Routing Algorithm
UW-ASN	Underwater Acoustic Sensor Network
UWSN	Underwater Wireless Sensor Network
VAPR	Void Aware Pressure Routing
VBF	Vector Based Forwarding
VBVA	Vector-Based Void Avoidance
WSN	Wireless Sensor Network
φ	Confidence Threshold
ξ	Localization Error

CHAPTER 1

INTRODUCTION

1.1 Background

Water is indispensable for human existence. More than 70% of the Earth's surface is covered by water. It regulates the Earth's temperature, helps in driving weather, acts as a channel for commerce and transport. Nonetheless, more than 95% of the ocean volume is yet to be explored and even more surprising, unseen by human eyes. The solid knowledge and understanding of the ocean are quite challenging and require arduous efforts. However, that is indispensable for the exploration and protection of this environment. Inauspiciously, the reality concerning technologies for large-scale data collection from the ocean is not exciting. Either sensor nodes without underwater communication capabilities or wired-interconnected underwater sensor nodes have been utilized for marine monitoring applications. These approaches are costly, not scalable and invulnerable to faults [1].

In this approach, UWSN has been capturing attention from scientific and industrial communities. The use of underwater sensor nodes, capable with wireless communication capabilities, have the power to detect real-time underwater monitoring and actuation applications, with an on-line system reconfiguration and failure detection capabilities [2].

Nevertheless, the effective data transmission to the surface sink is a daunting task due to the complex underwater environment. Though there are symmetries between terrestrial wireless sensor network (WSN) and UWSN, the later has gotten some characteristics which are unmatched and unparalleled to the former, such as high bit error rate, limited energy, data storage, three-dimensional network topology, and high transmission latency are some of the specialties that discriminate the two networks [3]. Radio Frequency (RF) has a unique characteristic of being a standard physical layer technology for WSN; however, due to the vulnerability of radio signals to the attenuation in the marine environment, it is unsuitable for implementation in UWSN [4].

Usually, the underwater sensor nodes are provided with acoustic modems to communicate with each other wirelessly and transmit the data from source to destination. Underwater communication links are influenced by high path loss, noise, multipath signal propagation, limited bandwidth capacity, Doppler spreading, and high power consumption. Furthermore, due to shadow zones, temporary connectivity loss can happen. Hence, the wireless link between neighbors can perform poorly or even be down at any given moment, which increases packet retransmissions, as an attempt to send data packets, and cause in more packet collisions, delay, and energy consumption [5],[6]. On the other hand, high-frequency radio and optical waves suffer from massive dissipation in the marine environment and are constrained to short-range applications only.

Low bandwidth and higher propagation delay are the distinguishing features of the acoustic channel, which make the UWSN environment unreliable in comparison to WSN [7]. Besides, UWSN carries a dynamic network topology in which nodes can move freely with water currents. Moreover, the path loss and Doppler spread also affect the performance of the acoustic channel. Because of these and many more distinguishing features, the routing protocols proposed for WSN cannot be directly executed in UWSN [8]; therefore, some novel protocols have been designed for UWSN particularly. Most of which are intended to handle an individual issue while not that productive with others and that's the reason there is a lack of common operational routing protocol heretofore.

Till date, localization, routing, and void avoidance are some of the unresolved issues in UWSN. It is essential to know the position of nodes in 3-dimensional topology to gain the potential applications of UWSN described above. Combining location information with the sample data collected by sensor nodes considerably increases UWSN capability, such as the Anti-Submarine Warfare system. If a node detects a submarine moment in the deployed area, then it can raise the alarm, however, if the location information is associated with the data, then the submarine can be traced, and necessary precautions can be taken more effectively. Apart from that, position information plays a vital role in the geographic routing protocols, which is an emerging technique for the underwater environment due to their scalability and diversity [9].

Acoustic communication is the typical physical layer technology for UWSN, which is characterized by low bandwidth and high propagation delay. Thus the localization techniques proposed for terrestrial sensor networks cannot be directly implemented into UWSN due to change in the transmission medium. Although some of the researchers have put their efforts to define a new localization technique for UWSN, however, some of these schemes are very good at handling one issue but not that useful with the others, and that's why we still do not have any state of the art practical localization scheme for UWSN till date [10].

The aforementioned constraints make WSN's protocols unsuitable for implementation in UWSN. For instance, the data collection techniques proposed for WSN results in poor performance when deployed in UWSN. Therefore, the existing WSN protocols were modified for the marine environment; however, the aforementioned constraints demand routing protocols designed explicitly for UWSN. The performance of a routing protocol is dependent on its data forwarding scheme. Data forwarding is a daunting task in UWSN, and there are several significant concerns like saving energy, handling node mobility, and so forth. The routing protocols can be mainly divided into three categories, i.e., proactive routing, reactive routing, and geographical routing. Proactive routing protocol maintains the static routing table, whereas the reactive routing protocols dynamically change routing decisions based on the network conditions. The prior causes large over-head, while the latter causes a considerable delay to create and maintain the routing path. On the other hand, geographic-routing suits the UWSN environment, where the routing decision is made based on node location information [11].

The broadcast nature of wireless networks has aroused opportunistic geographic routing like technologies, which best fit the UWSN environment for transmitting data from source to destination. In opportunistic routing protocols, the data is transmitted in a multi-hop fashion, in which the next-hop forwarding node is selected on the fly [12]. Opportunistic routing come along with its pros and cons, and that must be considered when designing a routing protocol for an underwater wireless network.

During the packet forwarding, if there is no intermediate node to relay the data packet, the packet may be dropped, although there could be a topological-valid path from the source to destination, this phenomenon is called the void problem [13]. Void communication area is a three-dimensional area carrying no valid forwarding node, which could be due to the sparse network deployment, temporary obstacle, and unreliable node or links. Due to the high cost of UWSN nodes, it may be deployed sparsely to monitor a large area, resulting in higher chances of creating a void area in the network. Moreover, the movement of the nodes due to water currents and the characteristics of the acoustic link may lead to packet failure and make the problem more challenging. Additionally, the void area may arise in the dense network due to temporary obstacles like a ship, which may block the communication between the two ends. Most of the existing routing protocols often ignore the void area handling or employ a high overhead method by exchanging too many control packet transmissions, which adversely affect the performance of the network [14].

1.2 Motivation

In the contemporary era, because of its many applications, UWSN has acquired umpteen attention from the research community. UWSN's applications are comprised of ocean monitoring, oil fields, and navigation assistance, disaster prevention, and submarine detection etc. UWSN mainly consists of underwater wireless sensor nodes, whose function is to sense the environment and transmit that data to one of the sink nodes, deployed on water surface [1]. These sink nodes collect the data and, after aggregation, forwards it to the onshore data center for further processing, as shown in Fig. 1.1.

1.2.1 Applications of UWSN

Underwater acoustic sensor networks are of great importance and have a broad range of applications. Some of these applications are:

- Environmental monitoring: UWASN can be used to monitor the environment of the seas. They can perform pollution monitoring, which can be chemical, biological, or nuclear. They can also be used to monitor the ocean current and wind. These underwater sensor networks can also improve weather forecasts,

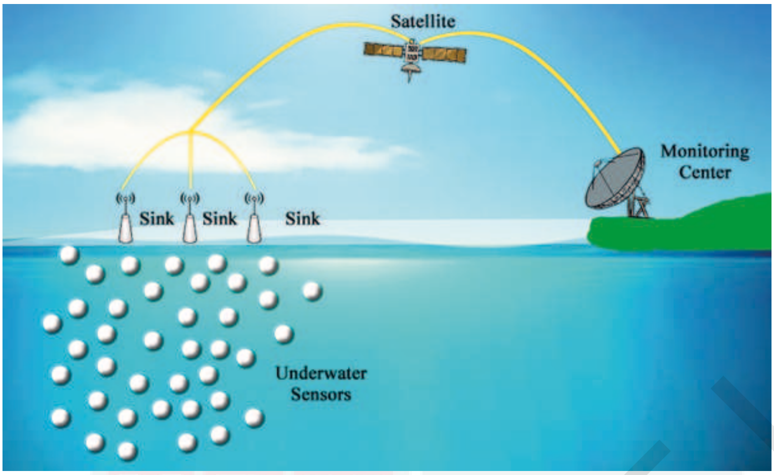

Figure 1.1: Typical UWSN Environment.

detect climate change, and predict the effect of human activities on the marine ecosystem.

- UNDERSEA EXPLORATION: Underwater sensor networks can be used to detect underwater oil fields and reservoirs. They can also determine routes for undersea cables and help in the exploration of valuable minerals.

- DISASTER PREVENTION: UWSN can help prevent disasters resulting from tsunami and submarine earthquakes by measuring seismic activity and can provide warnings to the coastal areas [15].

- EQUIPMENT MONITORING: Sensor networks can be used to monitor the expensive equipment immediately after deployment to assess deployment failures and detect problems.

- ASSISTED NAVIGATION: Underwater sensor networks can be used to identify hazards on the seabed and locate dangerous rocks in shallow water. They can provide help in the navigation of submarines.

- MINE RECONNAISSANCE: The UWSN can be used to perform a rapid environmental assessment and provide help in detecting mines.

1.3 Problem statement

UWSN enables real-time monitoring of the targeted ocean area, with the ability of remote configuration, and capability of supporting interaction with an onshore data center. As mentioned earlier, routing protocols proposed for WSN are not suitable for UWSN due to change in the transmission medium. Thus the required objective can be obtained by connecting the underwater devices by acoustic signals. In wireless communication systems, the underwater acoustic channel is distinguished as one of the rigorous communication media in use today. The underwater acoustic channel is quite expensive and unreliable. To achieve high data delivery ratio with low energy consumption is one of the significant challenges in UWSN. Moreover, a significant issue is to define the transmission range and data rate for the acoustic signal, which may vary from application to application. Furthermore, the system designed for deep-water may not work that useful in shallow water and vice versa.

Some of the issues that we considered in this dissertation are:

- Nodes localization in UWSN. Node's location information helps us to design efficient routing protocol, that can best utilize the available resources and extend the network lifetime. When considering UWSN, due consideration should be given to the issues imposed by the acoustic channel and the subsurface marine environment, such as node mobility. Although in most cases, sensor nodes are considered to be static, however in the actual scenario, they may be moving with water currents, and underwater activities are varying from 1-3 m/s. Further, the RF signal does not suite the UWSN environment and has to rely on the acoustic channel, which is characterized by low bandwidth, high bit error rate, and considerable propagation delay [10].

  Although localization in UWSN has been investigated during the past decade or so, and different localization algorithm has already been proposed. Some of these algorithms were designed explicitly for UWSN, while some are the extended versions of the localization schemes proposed for 2-dimensional WSN. The traditional range-free localization schemes proposed for UWSN [16], [17], which based on information flooding, produce huge communication overhead and are not suitable for this environment [16], [17]. Furthermore, range-free localization schemes cannot estimate the exact location coordinates; instead, it provides rough location estimates [18]. Whereas, in the proposed, range-based localization schemes [19], [20], [21], the ordinary node finds its location coordinates with the help of a mutual exchange of information. However, these schemes demand high network connectivity and do not perform well in the marine environment.

- Data aggregation and forwarding in UWSN. It is a challenging task to find and maintain the routing path in the dynamic UWSN environment, with the imposed energy restriction and the sudden topology change due to node failure. Due to the characteristics of the underwater environment and acoustic channel, the vast knowledge acquired in the context of $ad-hoc$ wireless networks, and

$RF - based$ wireless sensor networks cannot be directly applied in designing networking protocols for UWSN.

Although there are some routing protocols have already been proposed for UWSN but each of it carries its own limitations. The existing routing protocols [22], [23], [24], [25] depends on the size of the routing vector, however, determining the optimal threshold value for the routing vector is difficult, as it varies with network density. Whereas [26], [27] depends on the value of depth threshold, the larger the depth threshold, the fewer nodes are eligible for data forwarding, which results in lower packet delivery ratio and if the depth threshold is set to be small, many nodes may be eligible for packet forwarding, which leads to duplicate transmission.

- Void avoidance in UWSN. In a sparse UWSN environment, there may be no intermediate nodes to forward the data and may create void holes; determining and handling the void nodes is a challenging task and needs due consideration while designing a routing protocol. The acoustic environment and the mobility of nodes may create mobile void areas. Therefore, designing a routing protocol with a void avoidance technique to improve the performance of UWSN is crucial. Routing protocols like [25], [28] have mainly designed to address the void node issue in the data forwarding process. However, the former carries the inheriting problem of its dependency on the size of the routing vector, whereas, in the later nodes are forced for calculating its distance to neighboring nodes and rebroadcast this information frequently, that significantly increase network overhead.

1.4 Objectives

The general objectives of the thesis are to develop energy efficient routing protocols for densely deployed underwater wireless sensor networks. More precisely, we aim to design opportunistic routing protocols that could mitigate the drawbacks of the acoustic channel in UWSN. In order to get benefited from the $UWSN's$ applications, protocols of different layers and for different applications need to be proposed. The thesis mainly focuses on routing schemes; more specifically, it falls in three areas of $UWSN's$ routing, namely, localization of nodes, designing data forwarding scheme, and avoiding void nodes in routing path. The specific research objectives can be stated as:

1. Propose large scale hierarchical localization scheme for UWSN.

2. Propose data forwarding scheme for UWSN.

3. Propose void node detection and avoiding mechanism for UWSN.

1.5 Contribution

The contribution of the thesis are summarized as:

- New Localization Scheme: Localization plays a vital role in the designing and development state of the art routing protocol for UWSN. This contribution proposes a new localization scheme for large scale underwater wireless sensor networks, in which nodes are localized, and unique Ids are assigned to them.

- Designing Routing Algorithms: This contribution concerns the development of two routing protocols (the TORA and NA-TORA) for reducing disconnected nodes in sparse underwater sensor networks and improving energy efficiency and data delivery. In these protocols, disconnected and void nodes are resumed for the next transfer by rearranging the priority of the candidate set. This approach increases data delivery by improving network connectivity and routing efficiency. The novelties of the proposed protocols are twofold. Firstly, these are primitive position-based opportunistic routing protocols for mobile UWSN. Secondly, and most importantly, $TORA$ innovates in dividing nodes into STN and DTN, and their operations vary concerning their status. Lastly, This contribution consists in proposing an analytical framework to study the effects of transmissions and receptions on a node energy level. The proposed scheme was evaluated mathematically for both the best and worst-case scenarios.

- Implementation of Void Avoidance Scheme: This contribution presents the implementation details of a void avoidance technique on the proposed $NA-TORA$ protocol, called NA-TORA with VA. Which is supposed to discover void nodes proactively and thoroughly avoid the void area during packet forwarding.

1.6 Scope

The primary goal of this thesis is to explore existing routing protocols and to design energy efficient opportunistic routing protocol for UWSN. Various protocols are analyzed based on packet delivery ratio, energy efficiency, and end-to-end delay. The performance of the network is analyzed under different network scenarios, varying from very sparse to densely deployed network. The thesis presents the simulation results for the proposed routing algorithms, TORA, NA-TORA, and NA-TORA with VA in comparison to VBF [22], $HH-VBF$ [23], $H2DAB$ [29], $VAPR$ [28], and $VBVA$ [25]. The second goal of the thesis is to propose a large scale hierarchical localization scheme for UWSN, in which ordinary nodes are localized iteratively, and unique Ids are assigned to them.

1.7 Organization of the thesis

Each chapter in this thesis discusses the localization and routing issues in UWSN and presents the proposed solutions to overcome these problems. The remainder of the thesis is organized as follows:

- Chapter 2 elaborates on the different architectures of UWSN along with their pros and cons. Additionally, it summarizes the existing localization and routing protocols. Also, it gives an overview of the design and implementation of opportunistic routing protocols.

- Chapter 3 defines the research methodology and explains the network simulator used to evaluate the proposed schemes in comparison to existing schemes.

- Chapter 4 is dedicated to the proposed localization scheme in UWSN, where the proposed system is presented in detail. The proposed localization scheme is composed of two main sections. In the first section, ordinary nodes are localized iteratively to acquire their location coordinates within the network, whereas in the second section, the ordinary nodes are subdivided into two types based on their location parameters in the previous section, and each node responsibilities vary with its status.

- Chapter 5 and chapter 6 exclusively defines the proposed routing algorithms. In these chapters, two routing algorithms are presented for improving data delivery in UWSN, while minimizing the energy consumption and end-to-end delay. Both the routing protocols are implemented on the localization scheme presented in the previous chapter. However, the data forwarding techniques are different in these protocols, and which produces different results, when simulated. These chapters present the simulation results and discussions for the proposed schemes in comparison to some well-known existing routing protocols. Different parameters were used to evaluate the performance of the proposed schemes under a very sparse and densely deployed UWSN environment.

- Chapter 7 concludes the thesis and future work.

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