ENERGY EFFICIENT AND VOID AVOIDING ROUTING PROTOCOLS FOR UNDERWATER WIRELESS SENSOR NETWORKS

by

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DEDICATION

In loving memories of my dear father, ***Mohamed***

and my beloved sister, ***Zainab***

May ALLAH showers you with his mercy and forgiveness

Loved Always and with Heartbroken sadly Missed

((To ALLAH we belong and to Him we shall return)),

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Abstract

Underwater wireless sensor networks (UWSN) are an active area of research and development. The underwater environment is harsh; acoustic channel characteristics such as high attenuation and absorption are an important challenge for the implementation of UWSNs. Void holes in networks, where a node can receive but cannot transmit to any node other than the sender, also present a significant challenge. This dissertation is motivated by these challenges and investigates solutions for energy efficient and void avoiding routing protocols for UWSNs.

A proposed greedy routing protocol called Energy Efficient Depth-Based Opportunistic Routing (EEDOR) is designed and simulated. This protocol uses a novel holding time formula that incorporates both the priority of the candidate node and the depth difference between the packet sender and each candidate node of its forwarding set. The protocol uses a simple design that allows sensor nodes to form their forwarding sets by exchanging local information only. Nodes can collect information efficiently by listening and responding to forward request and forward reply messages. Simulation results show that the proposed protocol achieves significant energy savings as compared to popular protocols, thereby also extending network lifetime significantly.

A void avoiding protocol called the called Energy Efficient Depth-Based Opportunistic Routing with Void Avoidance (EEDOR-VA) is also proposed. The novelty of this technique lies in employing a hop-count to determine paths between the source node and sink(s). Trapped and void nodes are recognized and eliminated from node forwarding sets. This protocol is shown to have a high packet delivery ratio (PDR). The protocol is evaluated using two different sets of simulation settings.

Finally, the impact of the number of sinks and the sink deployment method on energy conservation and PDR is investigated. Simulation results show that using a deterministic multi-sink deployment can reduce the number of request and reply messages. As a result, the network overhead is reduced, decreasing the energy usage and increasing the PDR of the network.

List of Abbreviations and Symbols Used

1D UWSNs	One-dimensional Underwater Wireless Sensor Networks architectures
2D UWSNs	Two-dimensional Underwater Wireless Sensor Networks architectures
3D UWSNs	Three-dimensional Underwater Wireless Sensor Networks architectures
4D UWSNs	Four-dimensional Underwater Wireless Sensor Networks architectures
ACKs	Acknowledgment messages
ADCs	Analog to Digital Converters
ADV	Advancement Distance
AUV	Autonomous Underwater Vehicle
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CI	Confidence Interval
DBR	Depth-Based Routing protocol
DI	Directivity Index
$EBER^2$	An Energy Balanced Efficient and Reliable Routing Protocol
EDOVE	Energy and Depth variance-based Opportunistic Void avoidance
EECOR	Energy-Efficient Cooperative Opportunistic Routing protocol
EEDBR	Energy-Efficient DBR protocol
EEDOR	Energy Efficient Depth-based Opportunistic Routing protocol
EEDOR-VA	Energy Efficient Depth-based Opportunistic Routing protocol
ECR	Energy Consumption Ratio
EM	Electromagnetic
EPA	Expected Packet Advance
EPP	Expected Packet Progress

EVA-DBR	Energy-efficient and Void Avoidance Depth Based Routing
FLCOR	Fuzzy Logic-based Cooperative Opportunistic Routing for underwater acoustic sensor networks
FND	First Node Death
FwdREP	Forward Reply message
FwdREQ	Forward Request message
GEDAR	GEographic and opportunistic routing with Depth Adjustment-based topology control for communication Recovery
GOR	Geography-based Opportunistic Routing
GPS	Global Positioning System
HCREP	Hop-Count Reply
HCREQ	Hop-Count Request
HT	Holding time
HydroCast	A Hydraulic Pressure Based Anycast Routing Protocol
IoUTs	Internet of Underwater Things
IVAR	An Inherently Void Avoidance Routing Protocol for Underwater Sensor Networks
MCs	Microcontrollers
NCD	Node Closer to the Destination
NL	Noise Level
NT	Neighbor Table
OR	Opportunistic Routing
OREPP	Opportunistic Routing based Expected Packet Progress
PCR	Power Control-based opportunistic Routing protocol
PDP	Packet Delivery Probability
PFNs	Potential Forwarding Nodes
P_{holder}	Packet holder

RAM	Volatile memory
ROM	Non-volatile memory
ROVs	Vehicles Operated Remotely
Sec.	Second (time unit)
SL	Source Level
SNR	Signal-to-Noise Ratio
TL	Transmission Loss
TWSNs	Terrestrial Wireless Sensor Networks
uw-sinks	underwater sinks
UWSNs	Underwater Wireless Sensor Networks
VAPR	Void-Aware Pressure Routing
VHGOR	Void Handling using Geo-Opportunistic Routing in underwater wireless sensor networks
WDFAD-DBR	Weighting Depth and Forwarding Area Division DBR routing protocol
α	absorption coefficient
τ	maximal propagation delay of one hop
δ	global parameter
μ_{rj}	normalized neighbor fitness factor
ADV	Advancement Distance
d	distance
D_{diff}	the difference between the packet sender depth and the depth of its next forwarder
D_P	data rate
D_Prob	delivery probability
E_{fwd}	forwarding set selection energy
E_{idle}	idles state energy
E_{init}	sensor node initial energy

E_{Mean}	Mean Energy consumption per node
E_{resd}	sensor node residual energy
E_{total}	the total energy consumption
E_{trans}	data packet forwarding energy
f	frequency
FN	the number of transmitting nodes in one round
h	number of hops
k	spreading factor
L_{abs}	absorption loss
L_{size}	FwdReq/FwdRep message size
L_{spr}	spreading loss
m	number of the relay nodes in each hop
n	number of deployed nodes
NL	noise level
N_s	shipping noise
N_t	turbulence noise
N_{th}	thermal noise
N_w	wind noise
N_{trans}	Total number of transmissions
p	delivery probability
Pe	bit error rate
P_{recv}	receiving power
P_{sent}	the total number of generated packets
$P_{success}$	total number of distinctive packets received successfully at any of the sinks
P_{trans}	transmitting power
Rank	the node’s position in the sorted forwarding set list

R_{tx}	maximal transmission range of a sensor node
rounds	the number of simulation rounds
s	shipping activity
SNR	Signal-to-noise ratio
T	packet holding time
TL	transmission loss
v0	sound propagation speed in water
w	wind speed

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Chapter 1 **Introduction**

1.1 Overview

Technology is rapidly evolving, and networks are the most useful and popular innovation, as they are used in virtually every aspect of our lives on land, from banking to healthcare, government offices, postal services, education at all levels and types, and even at home. Hence, networks are becoming more prevalent in our daily lives. However, a large area of the earth (more than 2/3) is covered by water [1, 2] and only a small portion of that area is investigated. Over time, the underwater environment has been recognized as a significant source of food production, as well as a critical part of transportation, natural resource presence, defense, and sport/adventurous activities. To investigate the unattended underwater environment, exploiting the Underwater Wireless Sensor Networks (UWSNs) technologies in various areas of underwater studies has become an imperative, due to the increasing human requirements and needs. The harsh underwater environment, as well as its distinct features and characteristics, sets UWSNs apart from Terrestrial Wireless Sensor Networks (TWSNs). The underwater telephone, built for the US Navy after World War II (WWII) was one of the first underwater acoustic communication devices [3, 4]. The underwater telephone was developed to communicate with submerged submarines and employed the upper sideband of an 8.3-kHz suppressed carrier [5]. Since then, digital modulation/detection techniques pushed by technology development became the forefront of modern acoustic communications. Moreover, companies around the world are progressively engaging in modem development, and the legacy U.S. manufacturers such as Teledyne-Benthos, WHOI, and Link-Quest, are joined by new ones such as the French Thales and the German EvoLogics [6]. With these advances in technology, UWSNs became a hot topic and attracted more researchers' attention.

UWSNs rely on wireless sensor nodes in their communication. Most UWSN deployments require unattended function, which means the underwater sensor nodes must depend on electronic components (batteries) as a power supply to complete their electric operations (i.e. communication and data exchange). UWSNs must operate despite sensor nodes having severely limited and restricted usable resources, such as storage space/memory, energy and computational capability [7, 8]. The sensor's battery is likely to be destroyed or degrade more rapidly under extreme conditions, which could be found in deep water, such as low temperatures, salinity, chemical factors, etc. [9, 10], which effect the communication channel. The nodes' battery is not rechargeable and cannot scavenge solar power because the node is in an underwater environment, which remains unexposed to light. Replacing node batteries is an extremely expensive operation. Besides, UWSNs suffer from sensor fouling and corrosion [11]. Additionally, while in TWSNs the electromagnetic and optical waves are the most commonly used in the wireless communication between the sensor nodes, the underwater characteristics and sensor communication requirements rule out both of them. Both electromagnetic and optical waves do not propagate well and suffer from attenuation, absorption and scattering in underwater environment. High-power or massive antennas are needed since these signals attenuate quickly within a few meters (electromagnetic radio) or tens of meters (optical) [2, 10]. Therefore, the best existing solution for wireless communication in an underwater environment with satisfactory range, smaller amount of attenuation and higher reliability is the acoustic signal [12].

The unique characteristics and features of the aquatic environment, such as the network components and their limited resources, the acoustic communication channel, sparse UWSNs deployment, temporary obstacles [13, 14], node movement and node energy drain increase the probability of bit errors, packet loss and network partition. These effects have created the observed phenomenon known as the void area problem, attracting the attention of researchers. Addressing the constraints mentioned above along with the resulting void area problem is highly desirable to increase the network reliability and improve the performance of routing protocols.

1.2 Problem Statement

Motivated by the above-mentioned constraints and uniqueness characteristics of underwater environment and the acoustic channel, this dissertation is concentrated on two critical tasks that face the designers of routing protocols for UWSNs: energy conservation and the void area problem, both of which are addressed using the Opportunistic Routing (OR) technique. In this respect, the goal is to design, introduce, implement and evaluate OR protocols to accomplish the aims of energy conservation and address the void area problem.

The energy conservation is the most serious issue that needs to be considered during designing the communication protocols. The sensor’s available energy remains the most restricting factor since it influences a UWSN's functioning lifetime. Typically, the USWN lifetime is much shorter than that of TWSNs. This short lifetime of UWSNs is attributable to the sensor node's limited available energy as well as the communication processes. Thus, energy efficient communication protocols are highly desirable. Hence, conserving and/or efficiently consuming sensor energy and extending the lifetime of underwater networks is a critical task that has been a concern of the researchers since the early 2000's, and is still an active area of investigation to improve existing protocols or propose new works.

Therefore, the first part of this research introduces a novel OR protocol to address the energy conservation problem. The proposed protocol uses a greedy forwarding technique to advance collected data packets hop-by-hop to reach the sink(s). The protocol tackles energy conservation by minimizing the number of duplicate transmissions and reduces packet collisions through the novel holding time formula proposed to determine the transmission time of forwarding nodes. It can control the number of forwarding nodes by distinguishing the holding time of forwarding nodes with the same depth, through this technique we achieve minimum total energy dissipation and extend the network lifespan.

In the second part of this research, the void area problem is handled. In greedy routing, especially during the data packet forwarding process when a source/relay node cannot detect any capable node in its vicinity with a positive progress to continue forwarding the packet to reach the sink(s), the node can drop that packet even if a route exists between the source/relay node and the sink(s). This phenomenon is called the void area problem or can be called communication void as in [13] or local maximum as in [15] or local minimum as in [16] and it is another major concern in UWSNs. The source/relay node is called a void node if it is not within range of a sink and at the same time, it does not have any neighbor nodes with a positive progress that can keep sending the packet until it reaches the sink(s). It also can be called a trapped node if the only neighbor node with a positive progress in its transmission range is a void node or a node whose only path to nodes of a positive progress leads to a void node. That is, the only nodes with a positive progress that are in range of a trapped node are a void node or other trapped nodes.

The existence of the void area problem can significantly affect the efficiency of the greedy routing protocols and, as a result, the performance of the UWSN. Beside node energy drain, node failure and sparse 3D deployment, the uniqueness of the UWSNs and acoustic channel characteristics can cause more packet failures, which make the void area problem more challenging. Moreover, obstacles such as ships/ boats or underwater fauna and flora, can generate a temporary void area by obstructing the communication between some parts of the UWSNs. To this regard, the aim of this thesis is to propose, implement and evaluate a new protocol that can handle the effects of the void area problem on the UWSNs. Our novel OR protocol tackles the void communication between sensor nodes by bypassing the void area that occurs because one or more of mentioned above reasons. In our protocol, a new hop-count discovery mechanism that includes Hop-Count Request (HCREQ) and Hop-Count Reply (HCREP) is proposed to define the nodes' hop count, which is used to determine the forwarding path from the source node to the sink(s). The idea of the proposed Hop-Count procedure is to remove void/trapped nodes from the forwarding sets and exclude them from being a part of data forwarding process.

1.3 Contribution

The goals of this research effort are to contribute to and influence the field of data routing in UWSNs by introducing new OR routing protocols to enhance the UWSNs performance by addressing both energy conservation and void area problems. A number of contributions are made to the research in energy efficiency and void area in routing protocols for UWSNs. The following list summarizes these contributions, which will be explored in greater depth in the following chapters.

- Modeling of a new Energy Efficient Depth-based Opportunistic Routing protocol (EEDOR) [17]. EEDOR is an OR protocol that follows the hybrid forwarder set selection approach as classified in [1], where the forwarding set is selected in a cooperative way between the current forwarder node and its neighbors. EEDOR is implemented in a random distributed manner and the forwarding set candidates in each hop are chosen based on the local information collected through forward request/ forward reply messages exchange. Each forwarding set candidate is given a unique priority value to decrease the number of duplicate transmissions. As compared to DBR [18] and EEDBR [19], the simulation results of EEDOR demonstrate that EEDOR achieves the minimum number of transmissions and, as a result, the lowest energy dissipation in the network is accomplished, which enhances the lifetime of the network.

- Design of a novel void-aware protocol named (EEDOR-VA) [20]. EEDOR-VA is a reactive OR protocol that uses a hop count discovery procedure to update the hop count of the intermediate nodes between the source and the destination to form forwarding sets. EEDOR-VA is efficiently capable to eliminate all void/trapped nodes from the forwarding sets and data transmission process, thereby saving network resources and delivering data packets at the lowest possible cost. The extensive simulation results of EEDOR-VA indicate that the EEDOR-VA protocol outperforms DBR [18] and EEDOR [17] protocols in terms of packet delivery ratio (PDR), number of transmissions, it also outperformance DBR in term of energy consumption.

- Dealing with the void area and sensor nodes covered, we extend our work by investigating the deployment of multiple surface sinks. An extensive analysis of the impact of multi-sink architecture vs. a single-sink architecture and surface sink(s) deterministic deployment vs. random surface sink(s) deployment on routing protocols performance including energy conservation and packet delivery ratio. Accordingly, deterministic deployment of multi-sinks technique increases the number of sensor nodes covered by at least one of the sinks. As a result, this helps distributing the traffic load among more sensor nodes toward the sink(s). Balanced traffic load distribution leads to more uniform energy consumption among the nodes in the whole networks, which prolong the network stability period.

1.4 Organization of The Thesis

Chapter 1: presented above, covers a broad overview of background and motivation, as well as the contributions of the thesis. The remaining chapters are organized as follows:

Chapter 2: introduces an overview of UWSNs (i.e. architectures, nodes' hardware platform and applications) and UWSNs Routing Protocols Challenges. Opportunistic routing technique, UWSNs OR protocols classification and state-of-the-art for each class are also discussed. Finally, a comparison between UWSNs OR Protocols is presented.

Chapter 3: introduces a new Energy Efficient Depth-based Opportunistic Routing Protocol (EEDOR). The protocol stages are discussed in detail. The proposed protocol incurs low control message overheads since it does not require any global information and the one-hop information extracted through the forward request and forward reply messages between neighbors is used to form the forwarding set. The proposed holding time, used as a cooperative technique between the forwarding set candidates, ensures that when two or more candidate nodes drift at the same depth levels, the nodes will have different holding times before transmitting the data packet, resulting in a successful packet collision handling. Moreover, this protocol extends the network lifetime as well as overcomes the problem of energy consumption by reducing the number of transmissions.

Chapter 4: presents the void avoidance protocol for depth-based UWSNs OR routing protocol. Inspired by route discovery proposed in [21], Energy Efficient Depth-based Opportunistic Routing with Void Avoidance for UWSNs (EEDOR-VA) protocol proposes the hop count discovery technique. Sensor nodes are assigned their hop count through a hop count discovery process and only nodes with lower hop count numbers than the transmitter node hop count can be involve in the data packet transmission process. In this way, the trapped/void nodes are excluded from the forwarding set to ensure successful delivery of data packets. Hence, EEDOR-VA protocol reduces the cost of the packet being stuck in these unreachable nodes, which helping save their resources.

Chapter 5: depicts an extensive investigation on the impact of single-sink architecture vs. multi-sinks architecture in addition to deterministic surface sinks deployment vs. random deployment on routing protocols performance including energy consumption and PDR. The performance results of the proposed protocols (i.e. EEDOR and EEDOR-VA) related to energy consumption and PDR for these architectures and deployment techniques are provided in this chapter.

Chapter 6: concludes the thesis by summarizing the main contributions and findings and offers some future perspectives.

Chapter 2 **Background and Related Works**

2.1 Overview

With a large area of the earth (more than 2/3) covered by water [1], to investigate the underwater environment, exploiting the UWSNs in various areas of the underwater studies have become imperative due to the increasing human requirements and needs. However, these emerging UWSNs are a relatively new field that is quickly becoming a key component of underwater exploration, surveillance and military applications. The unique properties of the underwater environment and acoustic channel need the development of new specialized networking protocols for UWSNs. In this chapter, we discuss general aspects of underwater sensor networks (UWSNs) that were taken into consideration in this thesis and study previously proposed works related to the energy efficiency and void area.

This chapter is organized as follow: Section 2.2 presents some aspects of the UWSNs (i.e. underwater sensor nodes platform, UWSNs architectures, underwater applications, basics of acoustic channel, UWSNs routing and routing design challenges). Section 2.3 discusses the concept of opportunistic routing including OR construction blocks and classification. In Section 2.4, we survey the state-of-the-art of OR for UWSNs based on the literature review. The summary comparison between the reviewed OR protocols is presented in Section 2.5. Finally, Section 2.6 presents the conclusion of this chapter.

2.2 Underwater Wireless Sensor Networks (UWSNs)

In general, as defined in [22, 23] a UWSN is a fusion of wireless technology with micromechanical sensor technology having smart sensing, intelligent computing, and communication capabilities. Mainly, UWSNs contain several components such as vehicles and sensors that are deployed in a specific acoustic area to perform collaborative monitoring and data collection tasks [24, 25]. Information collected by underwater sensor nodes is transferred to surface stations called sinks (which can be static or mobile) equipped with both acoustic (to communicate with underwater devices) and RF modems (to communicate with other sinks as well as with on-shore stations). Furthermore, surface stations transmit data to a command center placed offshore [26] . The underwater sensors can be deployed in many different ways. Hence, prearranging the nodes wisely will help to prevent collisions and strategically constructing the network topology can assist in accomplishing high throughput.

2.2.1 Underwater Sensor Node Hardware Platform

The sensor node is the main UWSNs component that has the ability to sense the parameters, events or phenomena in the underwater physical world and transfer the sensed information to the onshore stations, where this information can be analyzed. A number of studies such as [27, 28, 29, 30] provide the components of the underwater sensor node. Therefore, we can see from the Figure 2-1 that underwater sensor node hardware is composed of the following fundamental elements:

- Controllers/ CPU: are electronic devices that include a processor, memory, and peripherals (i.e. Digital interfaces; ADCs; comparators; and timers). Because of these peripherals, microcontrollers are well suited to the design of embedded systems such as the underwater sensor nodes [30].

- Memory/ Storage: The two kinds of memories defined in underwater sensor nodes are: 1) Volatile memory (RAM) is critical to the operation of microcontrollers (MCs). The number of RAM bytes in an MC must be chosen in such a way that correct program execution is possible without risking UWSN operation. 2) Non-volatile memory (ROM) is often used for storing code and records. Non-volatile memory values ranging from 16 to 128 *kB* are used for code storage in low-power microcontrollers. However, data cannot be stored in this memory; instead, external memory circuits, such as EEPROM and FLASH memories, are used to store the information [30].
- Sensor interface circuitry: The controller/CPU is linked to an oceanographic instrument or sensor via the sensor interface circuitry [27]. The sensor interface circuitry converts the data collected from sensors into a digital data [28].
- Sensors: Underwater sensor nodes consist of sensors used to detect the underwater surrounding environment. Depending on the applications, sensors are used to measure the quality of water and help in studying its characteristics such as temperature, density, acidity, etc. [29].
- Acoustic modem: The underwater modem is used to transmit the data between the sensors. Various types of acoustic modems are used in UWSN, which provide low range to high range communication [28].

- Power supply: Since power scavenging is hard in the harsh underwater environment, the underwater sensor node is likely to be battery-powered to complete the missions assigned to it.

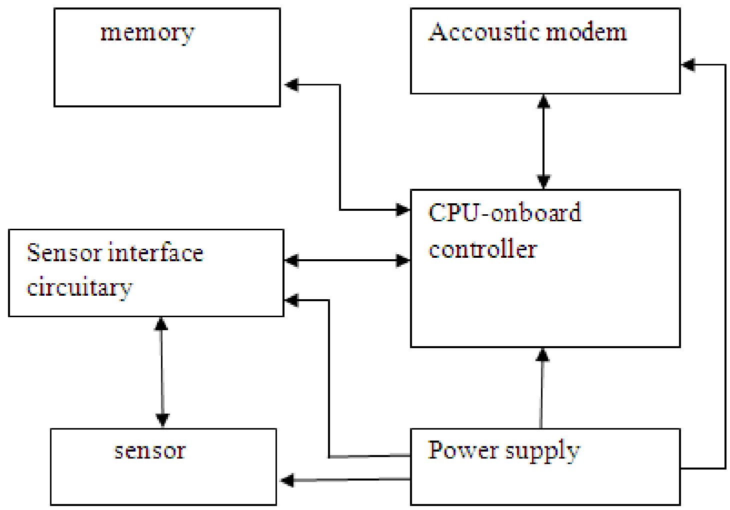


Figure 2-1: Internal Architecture Underwater Sensor Node **[29]**

Furthermore, depending on the application requirements, the underwater sensor node is built in different forms [30]. For example, current ocean measurements use ARGO [31], HydroNode [32] and autonomous underwater explorer (AUE) [33].

2.2.2 Underwater Wireless Sensor Networks Architectures

The topology of UWSN is a critical factor that influences the network's energy consumption, capability, and reliability [27]. Designing the network topology wisely helps accomplish high throughput and increases the network’s performance. In addition, to minimize node energy consumption, nodes in a large UWSN covering a sparse area must be deployed strategically.

In general, because of the high cost associated with installing UWSNs, underwater sensor equipment and the acoustic communication channel constraints, underwater missions are costly. As a result, building a highly secure network to prevent underwater node failures is important and desirable. Typically, there are two main architectures (Two-dimensional and three-dimensional) that are widely used in the literatures and described in [8, 24, 27, 34, 35] plus two extensions (One-dimensional and four-dimensional) on the main two that were described in [22, 23] and [28]. The following subsections cover the four UWSNs architectures.

A. Two-dimensional Underwater Wireless Sensor Networks architectures (2D-UWSNs)

Figure 2-2 illustrates a classification framework for two-dimensional underwater networks. The surface stations are equipped with both an acoustic transceiver to communicate with the deployed underwater sinks (uw-sinks) and radio transceiver to communicate with surface sink(s) and onshore sink(s). In the deep ocean, anchors are used to attach a group of underwater sensor nodes to the ocean floor and to form a 2D-UWSN at the ocean bottom. These anchored nodes are connected via wireless links to a single or multiple uw-sink, which are deployed underwater to collect the data by the anchored nodes. In the 2D-UWSNs, two acoustic transceivers are installed in uw-sinks. The first transceiver (called horizontal transceiver) is used to communicate between the uw-sink and sensor nodes and vice versa. The second transceiver (called vertical transceiver) is used by the uw-sinks to transmit aggregated data to some station on the water surface [8, 24].

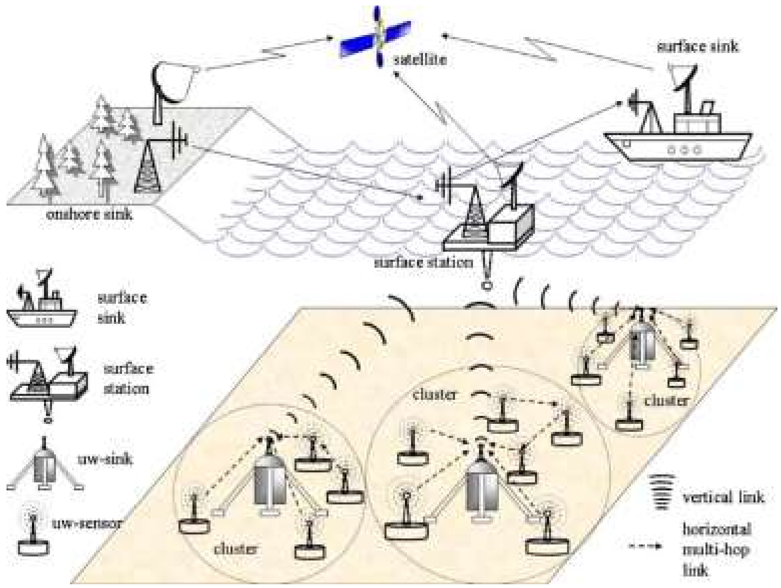


Figure 2-2: 2D Uwsns Architecture [27]

B. Three-dimensional Underwater Wireless Sensor Networks architecture (3D-UWSNs)

As the ocean's depth varies and the deepest place measured is more than 11km [36], many events and activities can occur between the surface and the ocean floor at different depths that cannot be detected by anchored sensor nodes at the ocean bottom. So, another structure known as Three-dimensional underwater wireless sensor networks architecture (3D-UWSNs) is used to sense and observe such phenomena and events. As illustrated in Figure 2-3, in the 3D-UWSNs sensor nodes drift at different depths [24, 34]. Every sensor node is anchored to the ocean floor and equipped with a floating buoy that can be inflated using a pump. The sensor node is driven towards the ocean surface by the attached buoy. The depth of the sensor can then be adjusted by changing the length of wire connecting the sensor to the anchor, which is controlled by an engine on the sensor that is controlled electronically [37]. In [22, 28], the 3D-UWSNs were presented as three types of inter-cluster communication of nodes at different depths, intra-cluster (sensor-anchor node) communication, and anchor-buoyant node communication.

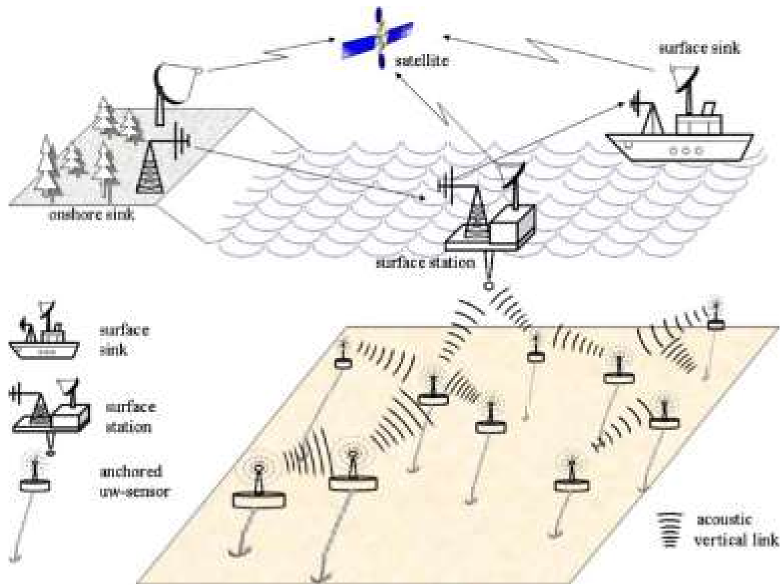


Figure 2-3: 3D UWSNs Architecture [27]

C. *One-dimensional Underwater Wireless Sensor Networks architectures (1D-UWSNs)*

In 1D-UWSNs, sensor nodes are installed independently. Each sensor node functions as its own network, sensing, processing, and transmitting data to the remote station. In this type of architecture, a node may be a floating buoy that can sense underwater properties for a certain period of time, then it floats back to the surface to relay that information to the remote station [28]. Alternatively, the node may be an Autonomous Underwater Vehicles (AUVs) that dives into the water, detects or collects underwater resources, and transmits the data to a remote station. The 1D-UWSNs has a star topology, where a single hop is used to transmit between the sensor node and the remote station. This topology can be used for acoustic, radio frequency, or optical communication [22].

D. Four-dimensional Underwater Wireless Sensor Networks architectures (4D-UWSNs)

The 4D-UWSN architecture is created by combining fixed UWSN (3D-UWSN) with mobile UWSNs [22]. The mobile UWSN is made up of underwater Vehicles Operated Remotely (ROVs) to collect data from anchor nodes and send it to a central station. ROVs may be autonomous submersible robots, aircraft, ships, and even submarines. Depending on how close the sensor node is to the ROV, each underwater sensor node can be autonomous in relaying data directly to the ROV [28]. The distance between the ROV and the underwater sensor node and the size of the data decide the contact scenario. Either acoustic or radio communication may be used. Since sensors transmit directly to the ROV, a sensor node will use radio links if it is near the ROVs and has a large data and will use acoustics links if it is distant from ROVs and has limited data [22].

2.2.3 Underwater Applications

Lately, UWSNs have received a lot of attention from researchers and industry [38] as a setting for oceanic research; and developing various potential applications is needed. Monitoring the underwater environment and the ocean's dynamic changes is becoming more difficult since the changes the underwater environment caused by disaster events as well as human needs and activities that cause pollutions and noises can greatly affect the environment characteristics and the communication channel. However, in order to conserve marine resources and achieve sustainable growth, these changes in the underwater environment must be successfully monitored. Moreover, climate change and increase in in-water activities may have significant impacts on oceanic life and ecosystems, which may significantly influence the terrestrial life and environment. Underwater sensor nodes have a sensor unit that give them the ability to interconnect with the underwater surrounding environment and provide a foundation for underwater sensor networks to be used in a variety of applications, including the ones mentioned below [10, 22, 23, 27, 28, 34].

- ***Underwater exploration:*** Oil fields and reservoirs under the water (whether deep or shallow) can vary from those on land. UWSNs will aid in the detection of underwater gas, oil fields or artificial lakes, monitor the underwater areas, as well as mineral exploration [28]. In addition, they are essential in determining routes for laying underwater cables.
- ***Environmental monitoring:*** In order to detect the most dangerous contaminants, advanced chemical analysis is used to monitor the marine environment. UWSNs can detect pollution, track ocean currents, improve weather forecasting, identify climate change, understand and predict the impact of human activities on marine environments, and examine ecosystems and biological systems [8, 22].
- ***Scientific applications/ Ocean sampling networks:*** Synoptic, cooperative adaptive sampling of 3D coastal ocean environments can be accomplished using underwater scientific equipment such as sensor networks and AUVs [39, 40].
- ***Disaster prevention:*** Natural underwater hazards include earthquakes, volcanoes and tsunamis, which can influence human life, on-land life and underwater life.

UWSNs can be widely used for detecting and monitoring these disaster events [26, 27, 28].

- ***Military surveillance:*** UWSNs are an essential component of military command, control, communications, surveillance, and reconnaissance used to detect, track and locate underwater obstacles or targets, which is the primary function of sonar systems, particularly in military applications that hunting submarines and mines [26, 40].

2.2.4 Basics of Acoustic Communication Channel

Acoustic signals are best suited for the underwater environment. There are two more alternatives that can also be used for transmitting wireless signals underwater (i.e. Electromagnetic (EM) and optical signals). EM signals have a short communication range at high frequencies because of the high attenuation and absorption effect [41]. While in EM communication the low-frequency propagation is appropriate, but it comes at the expense of high transmitting power and a large antenna height [27, 42]. Optical signals are a useful choice for point-to-point communication mainly in extremely clean water; they obviously achieve a very high data rate. However, these optical signals do not suffer from high attenuation, but they are affected by scattering [27]. Due to their short communication range, they are insufficient for large area distributed network constructions. Besides, accurate placement for the narrow beam optical transmitters is required [43, 27]. In summary, both EM and optical signals do not propagate well and suffer from high attenuation due to the underwater characteristics and sensor communication requirements

In contrast, acoustic signals are the most accurate and most suitable for densely deployed UWSNs. It enables omnidirectional transmission and distributed channel access while maintaining acceptable signal attenuation [12, 42, 44]. Regardless of all of the benefits, underwater acoustic signals provide a unique set of communication challenges. Temporary route losses, a high bit error rate, a limited bandwidth, and long propagation delays are all issues that the acoustic channel has to deal with [12]. Signal frequency affects path losses in addition to transmission distance. Low data rates are caused by severely reduced bandwidth, which is caused by both transmission spectrum and frequency [12, 45]. In short, due to the low attenuation of sound in water, the acoustic signals have been widely utilized in underwater communication systems. However, they can be negatively influenced by absorption and spreading loss, ambient noise, sound speed propagation and multipath propagation .

A. Spreading and Absorption Loss

The spreading loss (L_{spr}) of acoustic signals is caused by energy wasted when an omnidirectional source emits spherically across a body of water instead of being directed in a single direction. It is worth noting that the energy loss initiated by spreading in deep water is relative to the square of the distance and it is frequency independent. The spreading loss, in dB, can be calculated as:

$$L_{spr} = k \times 10\ log\ (d) \qquad 2\text{-}1$$

where d is the distance in meters and k is the spreading factor (k = 1 is cylindrical, k = 2 is spherical, and k = 1.5 in practical spreading).

The absorption loss (L_{abs}) of acoustic signals in seawater is subject to the temperature, salinity, and acidity, as well as the frequency of the sound wave. We use Thorp's expression since it is widely used in the publications [46, 47, 48]. According to [46], the absorption coefficient (α, in dB/km) which depends on frequency (f in kHz) can be defined and expressed mathematically as

$$\alpha = 0.11 \times f^2/(1+f^2) + 44 \times f^2/(4100+\mathbf{f^2}) + 2.75 \times 10^{-4} \times f^2 + 0.003 \qquad 2\text{-}2$$

The summation of these two factors (i.e. geometric spreading and absorption) is expressed in Equation 2-3 form the underwater attenuation or transmission loss (TL) of acoustic signal power [49].

$$TL = k \times 10\log(d) + \alpha d \times 10^{-3} \qquad 2\text{-}3$$

B. Noise

The noise levels in the ocean have a serious influence on the acoustic channel, they typically include all of the general background noise created by all sources, so that the contribution from a given source cannot be identified [50]; the noise levels then can be divided into [48, 51, 52],

- Ambient Noise: This noise is due to seismic and biological phenomena and water movement, which includes tides, current, storms, wind, and rain.
- Man-made noise: This is unnatural noise caused by human and shipping activity such as pumps, reduction gears, power plants, especially in areas encumbered with heavy vessel traffic.

Four sources of noises, namely turbulence ($N_t(f)$), shipping ($N_s(f)$), wind ($N_w(f)$), and thermal ($N_{th}(f)$) noises, are used to model the noise level. Equation 2-4 shows the calculation of these four factors in *dB/Hz,* respectively.

$$\begin{aligned} &10 \times \log N_t(f) = 17 - 30 \times \log(f) \\ &10 \times \log N_s(f) = 40 + 20 \times (s - 0.5) + 26 \times \log(f) - 60 \times \log(f + 0.03) \\ &10 \times \log N_w(f) = 50 + 7.5 \times (w)^{1/2} + 20 \times \log(f) - 40 \times \log(f + 0.4) \\ &10 \times \log N_{th}(f) = -15 + 20 \times \log(f) \end{aligned} \tag{2-4}$$

where *s* defines a shipping activity factor value ranging from 0 to 1, *w* gives the wind speed in *m/s* and *f* is the frequency in *kHz*.

Then, the overall noise is expressed mathematically in Equation 2-5

$$NL = 10 \times \log\big((N_t(f) + N_s(f) + N_w(f) + N_{th}(f)) \times B\big) \tag{2-5}$$

Where *f* in kHz and B is the bandwidth in Hz.

C. Propagation Speed of Sound

The low sound propagation speed is the most important physical factor influencing the performance of underwater networks. The speed of sound is assumed to be constant in most cases, but it is really affected by water properties such as temperature, salinity, and pressure [53, 49]. However, whenever any of these components rise, the speed of sound increases as well [12]. Near the ocean surface, the speed of sound is typically around 1500 m/s, which is four times faster than the speed of sound in air but five orders of magnitude slower than the speed of light [12].

D. Multipath Propagation

There are several paths from the transmitter to the receiver in underwater, known as multipath. Reflection at the borders (bottom, surface, and any objects in the water) and ray bending (since sound speed varies with temperature, salinity, and depth, sound waves always bend towards regions of lower propagation speed) are two essential causes of multipath development [54]. Multipath can have a negative impact on communications due to a significant delay spread (the difference of arriving time between the first and last paths at the receiver) that generates temporal distribution of a signal, which produces significant inter-symbol interference [49].

2.2.5 UWSNs Routing Protocols

Subsection 2.2.2 describes the possible network architectures for UWSN nodes deployed in an area of interest. To collect data whenever an event occurs, the underwater sensor nodes must be set up in such a way that the entire area of interest is covered. A route between any sensor node and a sink needs to be established for effective and reliable data transmission [55]. According to [4, 56], the sensor nodes can communicate either by: 1) direct link where the data packets can be sent directly from the source node to the sink or 2) through a multi-hop path where the data packets are forwarded by the relay nodes until they reach the sink. However, multi-hop communication suffers from the complexity of establishing a route, which effects network capacity, reliability and efficiency. Although comprehensive work has already been proposed for WSNs, the unique characteristics of the acoustic channel used in UWSNs motivate the proposal of new dedicated networking protocols for UWSNs. However, developing protocols specifically suited for UWSNs is challenging.

2.2.6 Main Challenges Facing Routing Protocol Designers

In this context, to better design the routing protocols for UWSN, a number of challenges that face the UWSNs routing protocol designers need to be take into account. These challenges are listed and briefly discussed below [34, 57, 58, 59, 60].

- ***Limited bandwidth and data rate:*** UWSNs suffer from limited available bandwidth (i.e. Acoustic waves use the frequency between a few Hz and tens of kHz) and low data rate (i.e. the transmission rate hardly exceeds 100 *kbps*). The limited accessible acoustic bandwidth depends on the communication range and acoustic frequency [59].
- ***High Propagation delay:*** The UWSNs use an acoustic channel for the communication between the underwater sensor nodes. In the acoustic channel, the propagation speed is five orders of magnitude lower than in the radio channel [58]. This high propagation delay (0.67 *s/km*) can significantly decrease the throughput of the network.
- ***High noise and interference:*** Two basic kinds of noise affect the underwater environment – man-made and natural. These noises are caused by water currents, machines, marine-mammals, and shipping. The noise under water is much more serious than in the terrestrial environment. The interference is essentially caused by the surface, the bottom, or animals and the contamination reflections [59].

- ***High bit error:*** Due to shadow zones caused by animals, water current and human-made noise, the acoustic channel suffers from high bit error rate and the temporary losses of connectivity [60].
- ***Limited resources:*** In UWSNs, sensor nodes are constricted resources devices (i.e. limited energy and memory). Therefore, after deploying the sensors in an underwater environment, it becomes difficult and costly procedure to replace or recharge the node batteries due to extreme underwater circumstances. Moreover, underwater sensor nodes are vulnerable to deterioration and damage due to corrosion and pollution [57, 61, 62].
- ***Topology changes:*** Due to the flow of water the underwater sensor nodes cannot stay in one location; instead, they move randomly, which give UWSNs a mobile or a changeable topology [58].

2.3 Opportunistic Routing (OR) Concept

Routing protocols are responsible for discovering and maintaining transmission routes. A novel OR is a promising technique, which was proposed for overcoming acoustic signal fading, high bit errors and losses due to shadow zones, limited bandwidth, high power consumption, and signal spreading to improve network function [63], which degrades routing protocol performance. The main concept of OR is to use the broadcasting nature of wireless networks, which allows multiple nodes to overhear the transmissions made by any in-range sensor node. Therefore, various underwater OR protocols have been suggested in order to enhance the communication in underwater networks.

In OR protocols, a subset of a node's neighbors will be selected as a next-hop forwarder set candidates. These nodes collaborate in a coordinated manner to continue forwarding the packet along toward the destination (sink) by using a prioritized technique according to the rules implemented by the protocol [1, 64]. This OR approach is preferable to the traditional multi-hop routing approach where only one single node is selected to act as a next-hop forwarder, to increase the probability of delivering the packet [1, 65, 66]. For example, if we assume that the delivery probability of each link (i.e. arrow in Figure 2-4) is p then the delivery probability (D_Prob) of the traditional one-hop routing protocol from the source node to the sink is also p. Likewise, in the traditional multi-hop routing approach, the D_Prob from the source node to the sink using h hops can be presented mathematically as

$$D\_Prob = p^h \tag{2-6}$$

On the other hand, if all the relay nodes can transmit the packet by using OR approach, the probability of delivering the packet to the sink is increased as explained in [55]. For OR with m possible relay nodes in each hop as shown in Figure 2-4 we can express the D_Prob mathematically as

$$D\_Prob = (1-(1-p)^m)^h \tag{2-7}$$

Where h is the number of hops between the node that originally generated the packet, and the final sink and m is the number of the relay nodes in each hop.

For clarity, let us give this example using Figure 2-4 below, let us assume that p=0.8, m=3, h=4. By using Equation 2-6, the delivery probability is 0.4096 for the traditional routing while by using Equation 2-7 we get a delivery probability 0.9684 for OR routing.

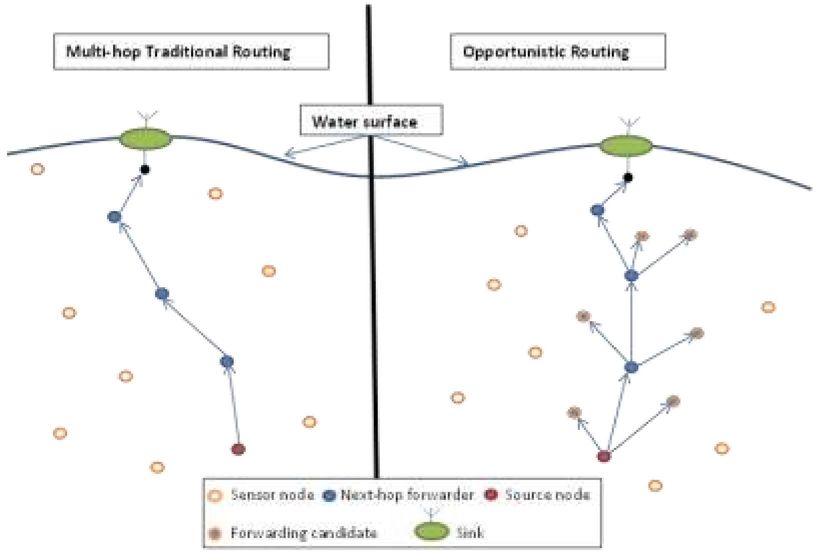


Figure 2-4: Multi-hop Traditional Routing vs. OR

Hence, by taking into account the advantage of the broadcast nature of the wireless transmission medium and using the OR forwarding technique, it has become possible to mitigate the effects of the underwater environment and its characteristics on the acoustic communication channel and improve the efficiency of the underwater acoustic physical links [1, 2, 66]. That is, the OR technique has been proposed to enhance network performance by reducing high bit errors and losses caused by limited bandwidth, high power consumption, and signal spreading [63]. Moreover, using OR reduces packet retransmission; retransmission will only take place when none of the next-hop forwarder set candidates received that packet. Taking into account OR features, a number of OR protocols for UWSNs have been developed in recent years. These OR protocols utilize multicast mode in which a single source node transmits its data to multiple nodes by utilizing more than one link at the same time forming the next forwarder candidate set.

2.3.1 OR Construction Blocks

The OR protocol technique is fundamentally built on two essential construction blocks: candidate forwarding set selection and candidate set coordination [1, 66]. These blocks are illustrated in Figure 2-5

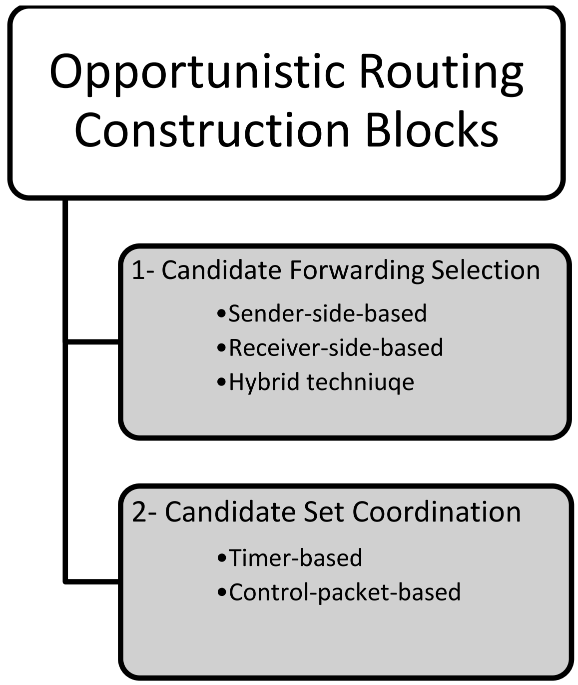


Figure 2-5: Opportunistic Routing Building Blocks for UWSNs

1. **Candidate Forwarding Selection**

The candidate set selection process is the first building block in OR protocol design. Electing a subset of nodes from the source's neighboring nodes to be the qualified set to carry on the packet and continue the forwarding procedure is the responsibility of this process. More generally, based on the next-hop forwarder node-selecting technique, the candidate forwarding set selection procedures can be classified into the three following categories [1, 66]:

i. ***Sender-side-based candidate set selection:*** in this category, the current forwarder node, which has a data packet to transmit, has the information of the sensor nodes in its neighborhood that are available through exchanging the beacon messages between the nodes in the networks. This available information can facilitate the sensor node's mission to determine its next-hop forwarder candidate set.

ii. ***Receiver-side-based candidate set selection:*** in contrast to the first category, in this category, when the neighbors receive the data packet from the sender, they check the header of the data packet for the information that can be used by these received node to determine which one is qualified for being a candidate node and which one is not. In this category, the responsibility of each neighboring node is to verify whether it will be in the next-hop forwarder candidate set or not.

iii. ***Hybrid candidate set selection:*** In this category, both the current forwarder node and its neighbor nodes work together in a cooperative manner through exchanging their information to determine the next-hop forwarder candidate set.

2. <u>Candidate Set Coordination</u>

The second and important block in designing an OR protocol is the coordination process. In this process, the nodes in the next-hop forwarder candidate set need to work together in a coordinated manner to continue forwarding the data packet until the packet reaches its destination. Here, the node with higher-priority (i.e. the most suitable node depending on the rules adopted by the protocol) will transmit the packet first, while other candidates with lower-priority hold on their transmission. If the higher-priority node fails to complete its transmission, the node with the second higher-priority will start its transmission, and so on until the packet is delivered to the destination.

This building process supports increasing the throughput of the network and the routing protocol accuracy, since by working in this coordinated manner the packet duplication, and the resulting energy consumed by the nodes due to unnecessary and redundant transmissions will be avoided. Besides, the total number of collisions can be reduced.

The coordination procedures between the candidates set can be divided into the two following categories as [1, 66].

i. ***Timer-based candidate set coordination:*** in this procedure, each candidate node has a holding time according to its priority. So, the candidate holds the received data packet from the source for a period of time. If the highest priority node successfully transmits the packet and if the other candidates receive an indication during their waiting time period, then they will suppress their transmission. Otherwise, the second highest priority node will start forwarding the packet when its holding time expires, and so on.

ii. ***Control packet-based candidate set coordination:*** in this procedure, a control packet exchange is used between the candidate nodes to coordinate with each other. Therefore, when a candidate node receives a packet, it replies with a short control packet. This control packet transmission is used to notify the current forwarder node that the packet has been successfully received, as well as to notify the other low priority candidate nodes that their transmissions should be suppressed.

2.3.2 OR Protocols Classification

Generally, routing protocols can be divided into different categories based on the principal features as in [4, 58, 59, 66, 67, 68, 69]. In the literature, a variety of OR protocols have been proposed to address different issues in UWSNs. As illustrated in Figure 2-6, we consider the node positioning information to classify the OR protocols for UWSNs into two main categories: Geography-based routing protocols and Pressure-based routing protocols.

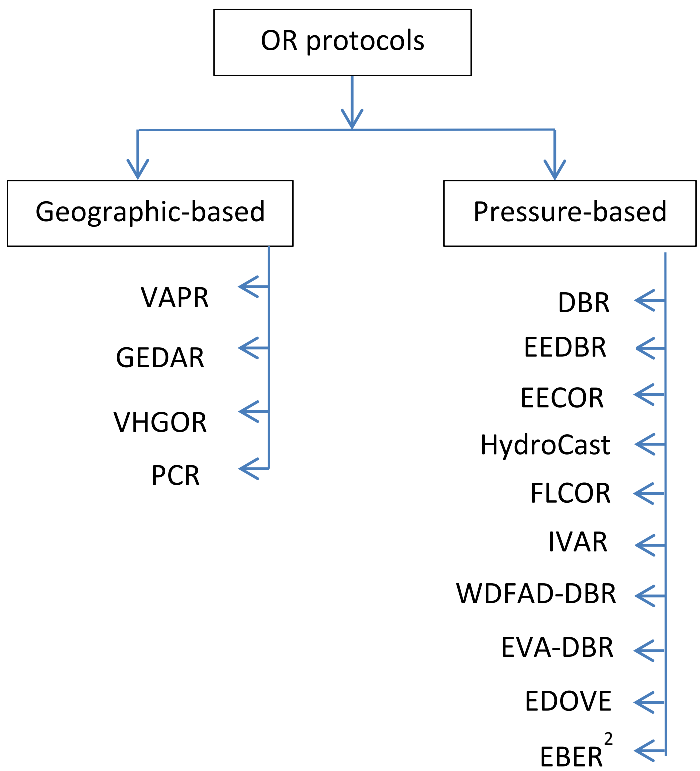


Figure 2-6: Classification of OR Protocols for UWSNs Based on Positioning Information

1. Geographic-based OR Protocols

In geographic-based routing protocols, the sensor node requires the location information of all the network nodes as well as the sink(s). Sensor nodes use this required geography location information to define the routes for data packet forwarding. A significant amount of energy is wasted in collecting this geographical information making the geographic-based routing protocols less energy-efficient. Global Positioning System (GPS) used in TWSNs cannot be directly utilized in UWSNs since electromagnetic waves attenuate rapidly underwater and cannot pass through several meters underwater [70, 71]. Since TWSNs use radio signals and UWSNs use acoustic signals in their communication, implementing the conventional TWSNs routing protocols promptly to UWSNs decreases network performance [27, 64, 72]. Geography location estimation can be attained using one of the appropriate localization techniques, such as those summarized in [70, 71]. Sensor nodes obtain geographic information to calculate the Euclidean distance between a source node *m* and the destination S_i (closest sink to node *m*) and from candidate node *C* to the destination S_j (closest sink to node *C*). Euclidean distances are used to determine the candidate ability to forward the packet to reach the destination by calculating the Advancement Distance (*ADV*), which given mathematically as

$$ADV = distance(m, S_i) - distance\left(C, S_j\right) \quad \text{2-8}$$

Where *m* is the sensor node, S_i denotes the closest sink to node *m*. *C* is a neighbor node of node *m*, it will be chosen as a forwarding set candidate if it makes a positive advancement distance to the sink S_j, which denotes the closest sink to node *C*.

For example, in Figure 2-7 below node C_1 will be chosen as a forwarding set candidate since it makes a positive advancement distance to the sink S, which means node C_1 is closer to the sink *S* than the source node *m*. On the other hand, node *m* eliminates node C_2 from its forwarding set due to the negative advancement distance to the sink *S*, which means that source node *m* is closer than node C_2 to the sink *S*.

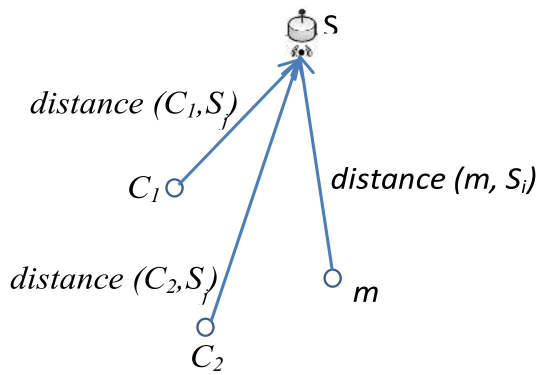


Figure 2-7: Forwarding Set Selection Based on Advancement Distance

2. Pressure-based OR Protocols

Obtaining the geography location information of an underwater sensor node is a challenging task because of the harsh environment and the acoustic channel features. Therefore, the Pressure-based routing protocols are preferred in UWSNs, as these protocols require only the information of the depth of sensor nodes for data routing. Since water pressure varies at various depths in the underwater world, the depth of each node can be determined locally by using a pressure sensor to measure the water pressure. Pressure-based routing protocols are based on this concept where each node is equipped with a low-cost pressure sensor that can measure the node's depth locally [73]. The depth information is used by greedy routing to define the next forwarding set. That is, sensor node C is considered as a next forwarding candidate for node m if the depth of candidate node C is less than the depth of sensor node m.

2.4 OR Protocols for UWSNs Literature Review

The related state-of-the-art OR protocols for UWSNs are reviewed in the next subsections.

DBR Protocol

The first OR protocol proposed for UWSNs using sensor node depth was the Depth-Based Routing (DBR) protocol [18]. In DBR, a depth threshold is implemented during the forwarding set formation to select the nodes with lesser depths than the source to continue the forwarding process. In addition, DBR uses the timer-based candidate set coordination technique and the holding time is calculated as shown in Equation 2-9 below based on node depth to manage the coordination phase between the forwarding nodes.

$$f(d) = \frac{2*\tau}{\delta} * (R - d), \delta \in (0, R]. \qquad 2\text{-}9$$

Where

$\tau = R/v_0$ is the maximal propagation delay of one hop (where R is the maximal transmission range of a sensor node and v_0 is the sound propagation speed in water).

δ is a global parameter, which chosen to be R in the protocol evaluation and d is the depth difference of the current node and the previous one.

However, using only the depth of the sensor nodes as a metric for forwarding set selection reduces the protocol's performance because the nodes having smaller depths are more often involved in the forwarding process. Hence, those nodes die sooner than the rest of the nodes in the network, which creates void zones. Moreover, a number of nodes may have the same depth, especially in the 3D-UWSNs architecture. Hence, using the nodes' depth only in the hold time calculation equation would result in the same transmission times being assigned to several nodes. Consequently, many redundant packets will be transmitted, which will consume a significant amount of node resources. Therefore, we can conclude that DBR is not suitable for dense networks in particular.

HydroCast Protocol

In [74], A Hydraulic Pressure Based Anycast Routing Protocol for Underwater Sensor Networks HydroCast protocol is presented. HydroCast applies only the local information of the topology to form a cluster with nodes excluding hidden-terminal nodes among them, and at the same time maximizing the Expected Packet Advance (EPA) of this cluster. In the HydroCast protocol, the current forwarder node needs to know the two-hop connectivity and the pairwise distances for the neighboring nodes to find its forwarding set. These are found by using the time of arrival technique, which is commonly applied in UWSNs. In addition, nodes in the forwarding set are prioritized using a distance-based timer, which means that when the forwarding set nodes receive a data packet, they each set their timer so the most distant node will have the shortest timer and so on, to help in arranging the transmission and suppress the collision.

HydroCast also proposes a *Local Lower-Depth-First Recovery* approach and *2-D Void Floor Surface Flooding for Recovery Path Search* for a recovery mode. Each void node (i.e. local minimum node as used in the paper) seeks out its neighbors to find a node with a lesser depth than itself; this less deep node could be another void node with a new recovery path or a node in a position that helps to resume the greedy forwarding. Figure 2-8 shows the recovery path in the HydroCast protocol.

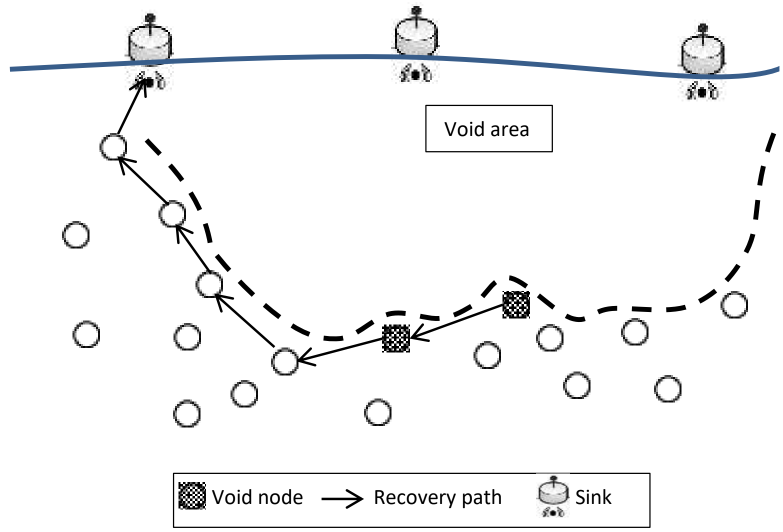


Figure 2-8: HydroCast Void Handling Technique

In the 3D network topology, nodes in a void area implement an expensive flooding method (hop-limited 3D flooding) to determine the best node that can resume the greedy forwarding or to find recovery routes to better forwarding paths.

However, the limited 3D flooding probability value is hard to estimate, the 3D flooding may include all the sensor nodes. As a result, the flooding will occur over the entire network topology. To overcome this limitation and improve the technique efficiency, they propose 2D flooding on the void floor surface, where the most appropriate set of nodes will be included in this flood. Therefore, nodes on the surface will use their local connectivity information to keep their void floor surface status under surveillance and accordingly forward the packet, while the other nodes that are not on the surface and controlled by surface neighbors will refrain from forwarding.

HydroCast addresses the void area issue using an OR approach, which also successfully enables increasing the packet delivery ratio with small end-to-end delays since a subset of the neighboring nodes simultaneously receive the data packet appropriately. But at the same time, as a result of using opportunistic routing, the HydroCast protocol suffers from redundant packet transmission where a data packet may be delivered to the sink multiple times, causing the depletion of network resources. In addition, implementing the recovery mode causes additional energy costs. Moreover, there is no evidence provided about the energy consumed by the pressure sensor in order to find its depth.

EEDBR Protocol

In [19] the researchers propose Energy-Efficient DBR protocol (EEDBR) to improve DBR performance by using both depth and residual energy of the sensor nodes in their protocol. In EEDBR, each sensor node knows the information of its neighbors (i.e. depth and residual energy); hence, the sending node selects the suitable nodes to form the next hop forwarding set among its neighbors with smaller depth than itself and sorts them in a list based on their depth. The selected nodes use their residual energy and their position in the sorted list of the forwarding set attached to calculate their packet holding time *T* using Equation 2-10 when they receive the transmitted packet.

$$T = (1- (current\ energy/initial\ energy)) * max\_holding\_time + p \qquad 2\text{-}10$$

Where *max_holding_time* is a system parameter (i.e. the maximum duration of a sensor node to hold the packet) and p is the priority value (p is initialized with a starting value and the priority value is doubled with the increase in the position index of the node in the sorted list) [19].

In EEDBR, the first node in the forwarding set transmits the received packet immediately without waiting, while the other candidates in the forwarding set wait for their holding time to expire to decide if they need to suppress or transmit their data packet.

VAPR Protocol

Void-Aware Pressure Routing (VAPR) is proposed in [75]. VAPR is an anycast soft-state routing protocol that was designed to address the void node issue in UWSNs. VAPR has two main stages: enhanced beaconing stage and opportunistic directional data forwarding stage. Instead of implementing a recovery mode for nodes in void areas, VAPR takes advantage of geographic routing and employs a periodic beaconing message that includes some useful local information about the sensor node.

In the enhanced beaconing stage, each surface sink broadcasts its reachability information to the underwater nodes. The enhanced beacon includes sequence number hop count and depth information, which is used to determine the next hop direction (upward or downward) to reach the nearest sink on the surface. The sequence number is used to update node information with the most recently received beacons. When a sensor node receives a beacon from a neighbor, it updates its neighboring table, compares its depth to the depth information received and updates its data forwarding direction upward/downward (i.e. DF_dir: UP/DN as illustrated in Figure 2-9) and hop count based on the nearest available sink.

If the sensor node receives a beacon with lesser hop count from a lower depth neighbor, then the sensor node data forwarding direction should be set as upward. Otherwise, it should be set as downward. This data forwarding direction is used by VAPR to identify void/trapped nodes as shown in Figure 2-10. When a void node is detected in the routing path by noticing that the data forwarding direction is swapped, the node uses the data forwarding direction of two hops to define the optimal overall route to the sink by deleting void nodes from its forwarding sets and making its own routing selection.

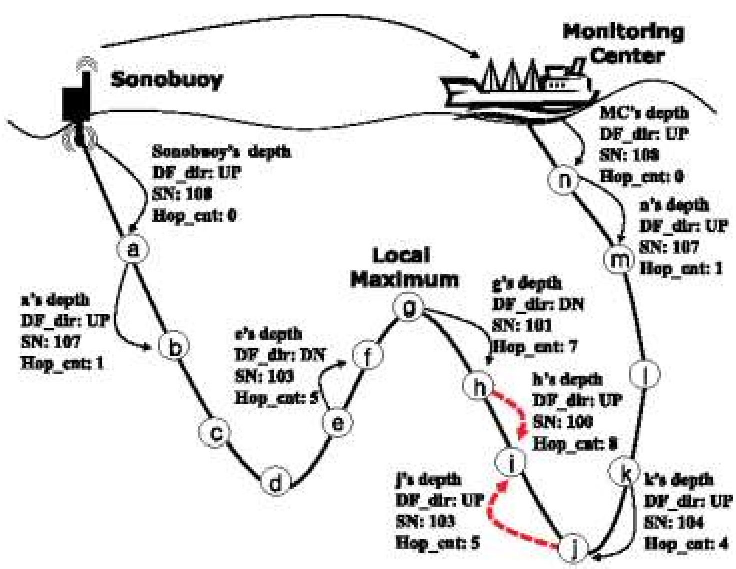


Figure 2-9: VAPR Enhanced Beacon Receptions [75]

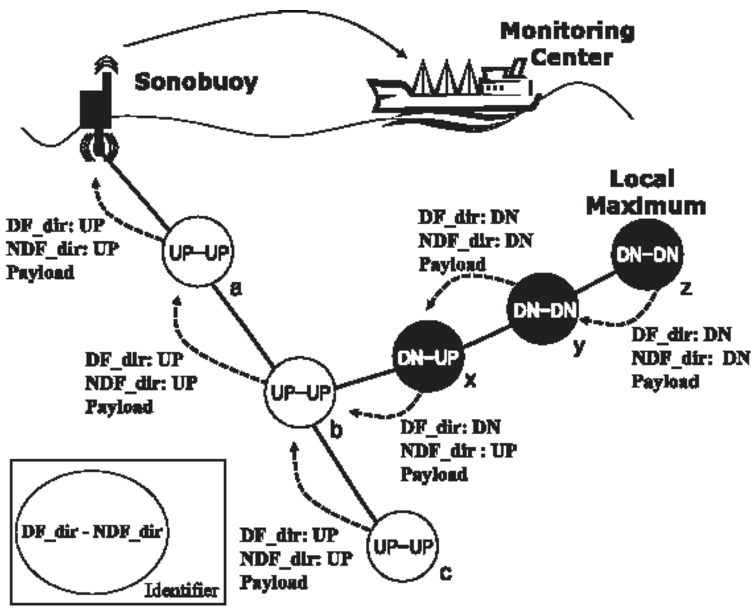


Figure 2-10: VAPR Directional Data Forwarding [75]

During the opportunistic data forwarding stage, each node holds the information of up to two-hop connectivity and aims to avoid packets being trapped in communication void areas. VAPR uses a simple greedy clustering approach and operates based on the data forwarding directional routes, which are the reverse direction of the beacon reception. A group of nodes among the neighbors of a transmitting node within the node's transmission range is chosen to avoid the hidden terminal problem. This group of nodes will form the forwarding set of the node; a list of the chosen forwarding set will be included in the data packet.

VAPR successfully bypasses the communication void region by using the data forwarding directional approach to remove trapped/void nodes from the forwarding sets. However, rebroadcasting node information periodically can significantly increase network overhead and exhausted node resources.

IVAR Protocol

An Inherently Void Avoidance Routing Protocol for Underwater Sensor Networks [76] is a receiver-based forwarding prototypical, so the forwarding node does not need to store its neighbor’s information. In IVAR, a hop-by-hop forwarding set selection technique is used to forward the data packets from the sensing node to the sink. To forward the packets, each packet holder uses local information of hop distance and packet advancement to determine its own forwarding set, and the nodes in these forwarding sets are arranged and given a priority based on two metrics: their hop count as a first metric and their depth as a second metric. IVAR uses beaconing messages sent from the destination to the source. This helps sensor nodes get the reachable information of the sink(s) and relay nodes. Therefore, the void nodes (yellow and red nodes as Figure 2-11 shows), will be excluded from the forwarding set of the sensor node and the route with a lower hop count will be chosen. Choosing a route with a lower hop count manages the energy consumption and reduces the packet delivery time. Besides, using the nodes’ depth can assist to prevent packet duplication. On the other hand, due to the protocol's broadcast nature and since qualified forwarding nodes may be distributed in various directions around the forwarding node, the protocol cannot completely suppress route and transmission duplication. The resulting duplication will cause the hidden terminal problem and consequently extra energy consumptions.

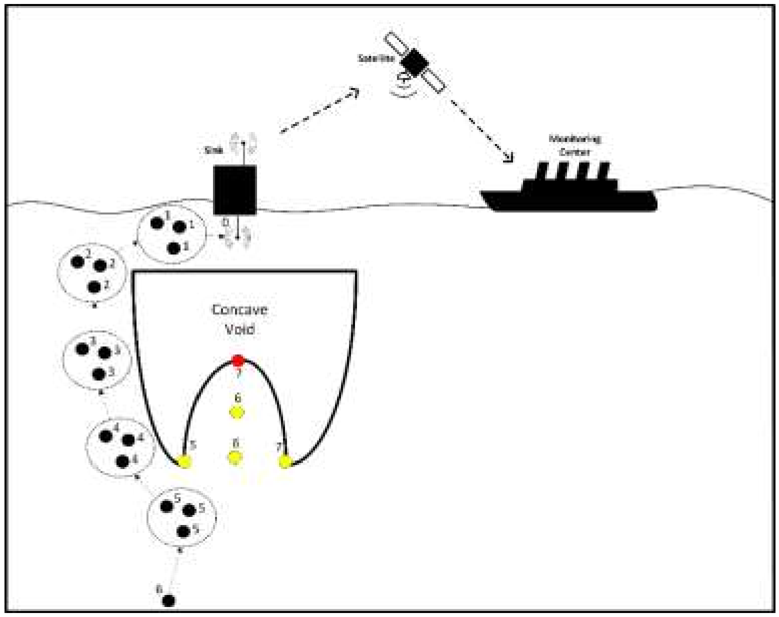


Figure 2-11: Void-Handling Technique **[76]**

IVAR uses a hop count periodic sink beacon to update the underwater nodes in the network with their proximity to the sink. Therefore, all the routes from the sink to the sensor nodes will be established in advance and all the routes that direct the packets to void areas will be excluded. However, the beacon interval has to be chosen cleverly because it has a great effect on the accuracy of the nodes' information and communication efficiency, which consequently will impact the network performance.

WDFAD-DBR Protocol

In [77] another pressure-based routing protocol was described in detail, namely Weighting Depth and Forwarding Area Division DBR routing protocol (WDFAD-DBR). To increase the reliability of the packet transmission and decrease the probability of the void areas. WDFAD-DBR uses the weighting depth difference of two-hop nodes to construct its routing decision. As presented in Figure 2-12, node S is a source node and the two forwarding candidate nodes with lesser depth are A and B. In the greedy protocol DBR, if node A is at a lesser depth than B, this gives A the priority to transmit first. Node B will suppress its transmission and drop the packet when it hears the packet from node A. However, a void area problem occurred since there are no nodes in node A's transmission area (S2) with less depth than node A to continue forwarding the packet. In contrast, WDFAD-DBR selects node B to forward the packet because it considers both depth differences, current depth difference (node B depth – source depth) and the difference depth of the expected next hop (node E depth – node B depth).

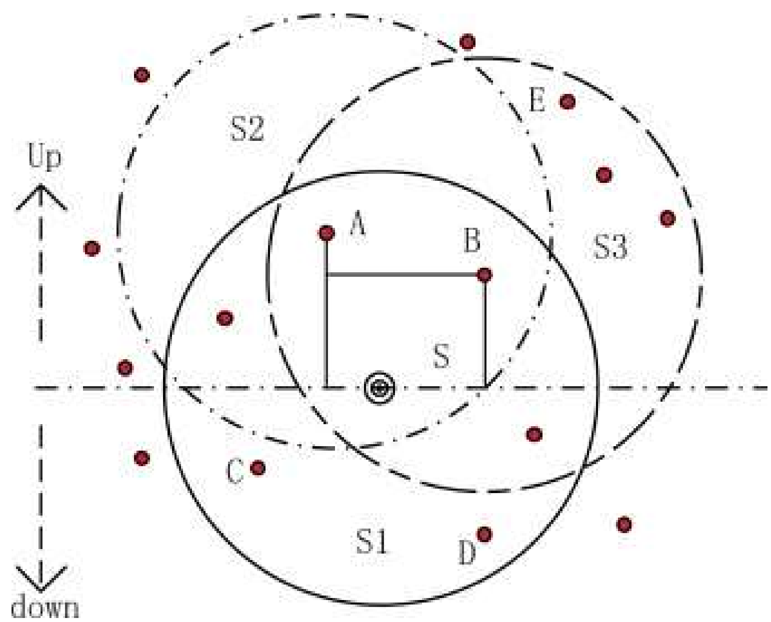


Figure 2-12: Void Area Problem [77]

In WDFAD-DBR, the void nodes can remove themselves from the data packet routing to increase the opportunity of the other candidates in the forwarding set to forward the packet. In addition, to control the number of forwarding nodes, WDFAD-DBR divides the forwarding area into a constant primary forwarding area (Reuleaux triangle), and two auxiliary forwarding areas that might be extended or shrunk depending on the node density and the quality of the channel. In terms of energy consumption, on one hand the auxiliary forwarding area is divided into a number of smaller sub-areas to help reduce energy consumption due to duplicate packet transmissions. On the other hand, the periodic neighbor requests and the corresponding Acknowledgments (ACKs) in a reply to each control packet exhausts node energy. To bypass a void area, WDFAD-DBR successfully detects the void nodes and excludes them from the forwarding procedure. However, the protocol fails to detect trapped nodes in advance. Moreover, when a fixed primary forwarding area is implemented by the protocol, the flexibility of the routing might be restrained to choose and adjust the forwarding nodes under various conditions.

GEDAR Protocol

In [78], GEographic and opportunistic routing with Depth Adjustment-based topology control for communication Recovery (GEDAR), utilizes the greedy forwarding technique by knowing the position information of the current forwarding node, its neighbors, and the known sink. GEDAR is a sender-side OR technique, where the forwarding set is determined in each hop by the sender node. Initially, GEDAR uses a greedy opportunistic forwarding mode to route the packets. Once a node has gathered some data and needs to transmit it to the sink(s), the node includes its forwarding set candidates list of IDs in the data packet header and broadcasts the packet to its neighbors. When a neighbor node receives the transmitted packet, it checks whether its ID is in the packet header or not. If it is not a forwarder candidate node, it simply drops the packet. Otherwise, it calculates the holding time to decide when it can transmit the packet. This procedure continues until the packet is delivered to the sink(s) on the water surface. If the packet is trapped in a void node, the recovery mode is applied by GEDAR. In the recovery mode, when the packet is stuck in a void node, the protocol deals with this void area problem by taking advantage of a network topology control strategy. In the network topology control, any node in a void area can move in a vertical direction to bypass the void area by adjusting its depth and can communicate with other nodes to resume the greedy forwarding. Therefore, the void node first discontinues sending the gathered packets and starts to calculate a new depth that will allow it to continue its OR greedy forwarding to deliver the data packet to the next hop. For example, as illustrated in Figure 2-13, node V can move vertically from depth D_1 to depth D_2 to be able to communicate with next forwarder.

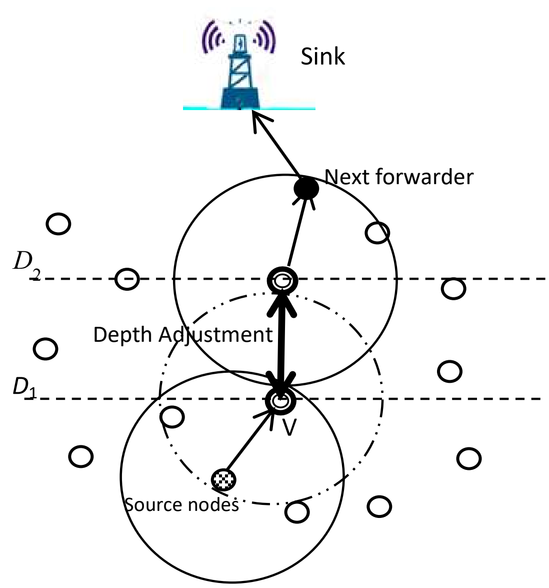


Figure 2-13: Depth Adjustment Technique

The recovery technique used by GEDAR helps to bypass the void area and as a result improves the network connectivity and increases the packet delivery ratio. On the other hand, in terms of energy consumption, this Depth Adjustment technique exhausts a significant amount of energy in physical movement to adjust the network topology, which causes nodes to deplete their energy rapidly, resulting in energy holes and reducing the network lifetime.

FLCOR Protocol

Based on the DBR protocol, authors in [79] propose the Fuzzy Logic-based Cooperative Opportunistic Routing for Underwater Acoustic Sensor Networks (FLCOR) protocol, which uses a fuzzy logic approach to improve network stability. Similar to other depth-based routing protocols, FLCOR uses the node's depth to select the forwarding set candidates. Accordingly, the sensor nodes with lesser depth than the source can be considered to form the forwarding set and relay the packet towards the surface sink. The protocol also adopts a fuzzy logic system to select the best forwarding node from the forwarding set to continue forwarding the packet to reach the sink. Two fuzzy inputs are used: energy consumption ratio, ECR, (the ratio between the residual and the initial energy of the sensor nodes) and the packet delivery probability, PDP, along with nine if-then fuzzy rules to get one output, called chance. The node in the forwarding set with the maximum value of chance has the highest opportunity to be nominated as the best forwarding node for the current transmission. This fuzzy logic method works well on the network stability and prolongs the network lifetime which means that the nodes' energy consumption is reduced. On the other hand, there are no other results provided on the paper to support the energy efficiency.

VHGOR Protocol

Void Handling using Geo-Opportunistic Routing in underwater wireless sensor networks (VHGOR) [80] adopts Geography-based Opportunistic Routing (GOR) to forward data packets to reach the destination over multi-hops. It is a heuristic protocol that implements two metrics to form optimal forwarder selection. The first metric is the Opportunistic Routing based Expected Packet Progress (OREPP) that is calculated based on the difference between the geographic distance between the source and destination, and the geographic distance between any node and the destination, residual energy and packet delivery probability. The OREPP metric tries positive advancement of the data packets towards the destination. The second metric is the Node Closer to the Destination (NCD); NCD can be defined as the best node with maximum OREPP to forward the current packet. VHGOR uses a greedy forwarding approach to advance the packet towards the destination and if a packet gets into a void node, the protocol switches to the void mode. VHGOR handles the void problem using the two following techniques:

1- ***Convex void handling:*** if the packet is trapped in the NCD node, VHGOR eliminates the current forwarder and attempts to re-establish the convex structure with the remaining neighboring nodes found in the Neighbor Table (NT) to find an alternative route to forward the same packet to the destination.

2- ***Concave void handling or recovery mode:*** when a packet is stuck in a node that has no neighbors with lower pressure level, which means that its NT entry is empty, the void becomes concave. VHGOR handles the concave void by redirecting the packet along the recovery path that operates from downwards to upwards to re-route the packet through an alternative path to reach the destination. The concave void node re-sends the packet to its previous sender, which chooses the next NCD node from its NT to continue forwarding the same packet.

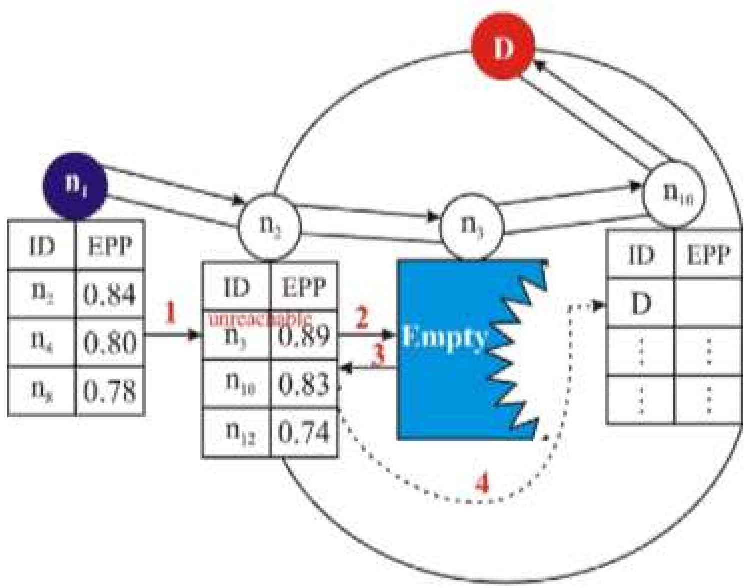


Figure 2-14: VHGOR Recovery Mode [80]

Figure 2-14 shows the forwarding packet route and recovery mode implemented by VHGOR. Node n_1 chooses node n_2 as a next forwarding node, since it has the largest Expected Packet Progress (EPP) value in its neighbor table (direction number 1 in the figure). Following the same steps, node n_2 selects n_3 as a next forwarding node and sends the packet to it (direction number 2 in the figure), but because n_3 is void node and its neighbor table is empty, node n_3 sends the packet back to n_2 (direction number 3 in the figure). Node n_2 then selects the next node in its neighbor table to be the next forwarder n_{10} (direction number 4 in the figure). Finally, node n_{10} deliver the packet to D since destination D is in n_{10} neighbor table.

EECOR Protocol

Another depth-based protocol called Energy-Efficient Cooperative Opportunistic Routing protocol (EECOR) was proposal in [81]. The authors first used a sender-based opportunistic routing technique to identify a group of relay nodes (next hop forwarding set) that can transmit the data packet upward to reach a single sink on the water surface; the selected relay nodes must have the maximum sensor node advancement and the maximum Packet Delivery Probability (PDP). To determine nodes' advancement they present a normalized neighbor fitness factor represented as

$$\mu_{rj} = \frac{D_i - D_{rj}}{R_{max}} \qquad \text{2-11}$$

Where D_i -D_{rj} represents the difference between the depth of the source node D_i and the neighbor relay nodes depth D_{rj}, R_{max} is the maximum transmission range of the sensor nodes. Then they applied a fuzzy logic technique that uses two variables: PDP and Energy Consumption Ratio (ECR) to determine which forwarding node would forward the data packet first. Using fuzzy logic, each node in the forwarding set is assigned a value. The value determines the chance that the node will forward the packets. The node in the forwarding set with the maximum value of chance from fuzzy logic output has the greatest opportunity of being nominated as the best forwarding node for the current packet transmission. The remaining relay nodes will suppress their transmission and calculate their holding time (T_{Hrj}) as

$$T_{Hrj} = \left(1 - \mu_{rj}\right)(\tau_{max}) + \frac{R_{max} - \left|\overrightarrow{d_{rj}}\right|}{V_{sound}} \tag{2-12}$$

Where τ_{max} and V_{sound} are the maximum propagation delay and the acoustic signal propagation speed, respectively and $\overrightarrow{d_{rj}}$ refers to the distance between the source node and the neighboring relay node.

EECOR reduces the duplicate packet transmission by using fuzzy logic techniques to choose only one node with a maximum chance value to be the best forwarding node to forward the packet. This technique conserves node energy while reducing packet collisions. However, if the first forwarding node fails to send the packet, the protocol must use fuzzy logic again to pick the second forwarding node. This process will be repeated until one of the relay nodes successfully forward the packet to the next-hop destination and that will exhaust the source resources. Furthermore, EECOR does not take into account the multi-sink architecture, which causes nodes located closer to the single sink to deplete their batteries more quickly.

EVA-DBR Protocol

The Energy-efficient and Void Avoidance Depth Based Routing (EVA-DBR) protocol was proposed in [82]. EVA-BDR is a routing protocol that consists of two phases: the updating phase and the routing phase. In the updating phase, the protocol depends on periodically broadcasted information from the neighboring nodes that are one-hop away from the source node for void detection and bypassing in the routing phase. Initially, in the network, all the nodes are homogeneous nodes. However, in the updating phase, the void and trapped nodes are detected over time by the broadcasted information. Each regular node will choose its best candidate node among the neighboring nodes with lesser depth, in terms of the Expected Packet Advancement (EPA), to be used as a reference node in the opportunistic data forwarding [82]. In the routing phase, to increase the packet delivery probability in each data transmission operation, all the detected void and trapped nodes take themselves out of the forwarding set; this procedure will increase the opportunity for the other regular nodes in the forwarding set to forward the packet. In addition, the forwarding area can be re-sized depending on the density of the network as presented in Figure 2-15 and all the qualified nodes will set their forwarding timer to forward the data packet. This forwarding time should guarantee a priority-based scheduling of the nodes in the forwarding set and should suppress the duplicate packets.

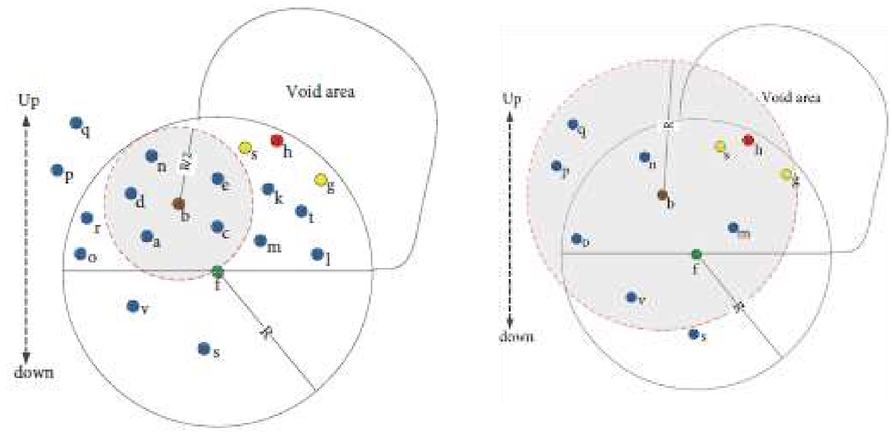


Figure 2-15: Re-size Forwarding Area Sparse Network (Right) and Dense Network (Left) [82]

Since the nodes in the network do not need to send an ACK message as a reply to their control packets, the energy consumed per node will be reduced somewhat. In contrast, the protocol may exhaust node resources, resulting in a decrease in node and network lifetimes, by allowing periodically broadcasted information and duplicated transmissions so that the packet delivery probability in a sparse network is increased. Also, excluding some of the nodes from the forwarding set may have an effect on the energy consumption and reliability of the network. Moreover, maintaining the neighboring table and the 2-hop information will adversely affect the limited resources of the node (i.e. energy, memory).

EDOVE Protocol

In this section, we review the protocol presented in [83] called Energy and Depth variance-based Opportunistic Void avoidance (EDOVE) protocol. EDOVE was proposed based on WDFAD-DBR, the work presented in [77]. The protocol handles the void area problem by choosing the forwarder candidates, among the total distributed nodes, which have a large residual energy and have several nodes in their transmission range (neighbors). To get these useful nodes' information, each node in the network topology exchanges its information with its 1-hop neighbors through the neighbor request and neighbor acknowledgment packets, and each node has to maintain its neighbor table. When the sender has a data packet to transmit, all its neighbors naturally receive that packet, then that packet has to be transmitted through any of these neighbors to the next hop or to the destination (sink(s)). Since these receiving nodes have different residual energy, EDOVE takes this diversity into account. In contrast to WDFAD-DBR, EDOVE uses the two hop depth differences (d_i^{NF}), the normalized residual energy of the node (E_i), next hop depth difference to the source (d_i) and the depth difference variance between the neighbors to compute the holding time. The holding time parameters are shown in Figure 2-16.

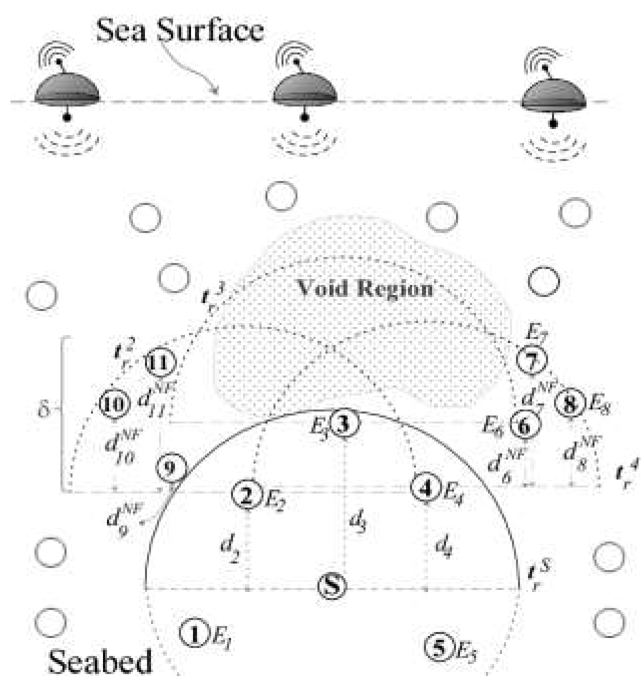


Figure 2-16: Holding Time Calculation Parameters [83]

Finally, EDOVE selects a receiving node based on its residual energy, depth difference to the source, depth difference to its neighbors, and variance in depth difference with its neighbors. This decision is made by using these parameters in calculating the holding time. By taking into account more parameters, the protocol saves more energy, avoids packet collisions, and expands the network's lifetime. However, in dense networks or in the case of enlarging the size of the network, the probability of duplicated packet transmission rises because the number of nodes with the same depths increases, making their estimated holding times almost the same, which increases data packet traffic and, as a result, the energy consumption increases.

EBER^2 Protocol

An energy-efficient and reliable protocol named as An Energy Balanced Efficient and Reliable Routing Protocol (EBER^2) has been proposed in [84] to address the void holes. The protocol adopts the Potential Forwarding Nodes (PFNs) concept to address WDFAD-DBR drawbacks. In some cases, WDFAD-DBR suffers from void holes problem because it does not take into account the PFNs for the second hop, resulting in high duplicate packets and collisions that degrade protocol performance and efficiency. In EBER^2, the network architecture consists of three types of sensor nodes (sink nodes, anchored nodes, and relay nodes) as shown in Figure 2-17. The nodes deployed on the water surface are sinks. Anchored nodes are attached to the seabed and stay static in their positions. The relay nodes are deployed at a different water level and are mobile.

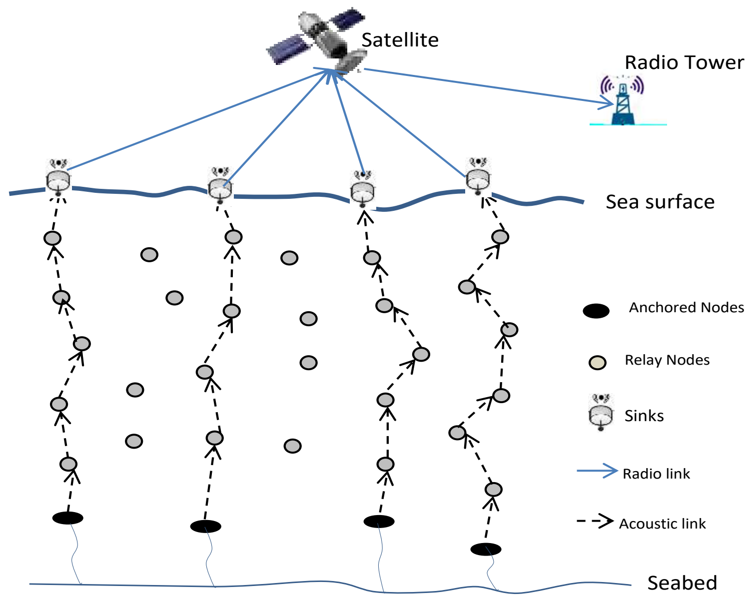


Figure 2-17: EBER^2 Network Topology

To address the WDFAD-DBR shortcomings, the authors of EBER^2 consider three parameters as criteria for selecting the next forwarder. The first parameter is the weighting depth difference of two hops: using the depths of the first two hops for selecting the next forwarder node reduces the chance of the void area problem in the network. The second parameter is the number of PFNs, which are defined as the nodes that lie in the upper hemisphere of the transmission range of the source node. If a node does not have any PFNs that means this node is a void node, thus it is excluded from the next forwarding set and increases the network reliability. The third parameter is the residual energy: to avoid duplicate packets, they use the residual energy of the nodes to give different holding times to PFNs that have the same depth. These three parameters assist in forming the next forwarder set and eliminate void nodes from being selected as next forwarder candidates, avoiding duplicate packets and the resulting collisions, supporting energy efficiency, increasing the packet delivery ratio and extending the lifetime of the network.

Furthermore, the $EBER^2$ protocol deploys two additional embedded sinks in the underwater area of interest, which have high traffic density, as shown in Figure 2-18, to help these nodes in communicating with the embedded sinks and delivering data packets to them rather than traveling through a long path to reach the sinks on the surface. In general, this technique improves the network packet delivery ratio and reduces the energy consumption, since the nodes located in these high traffic areas transmit the received packet to the nearest embedded sink instead of transmitting further to the surface. On the other hand, due to the communication of the embedded sinks with the on-surface sinks via high-speed optical fiber links, the communication cost increases. In addition, $EBER^2$ implements a transmission energy adaptability technique to allow nodes nearer to the sinks to lower their transmission power level based on their distance from the nearest sink. This helps the nodes near to the sinks from depleting their energy fast due to being involved in most of the forwarding procedures, which addresses the void area caused by the death of these nodes.

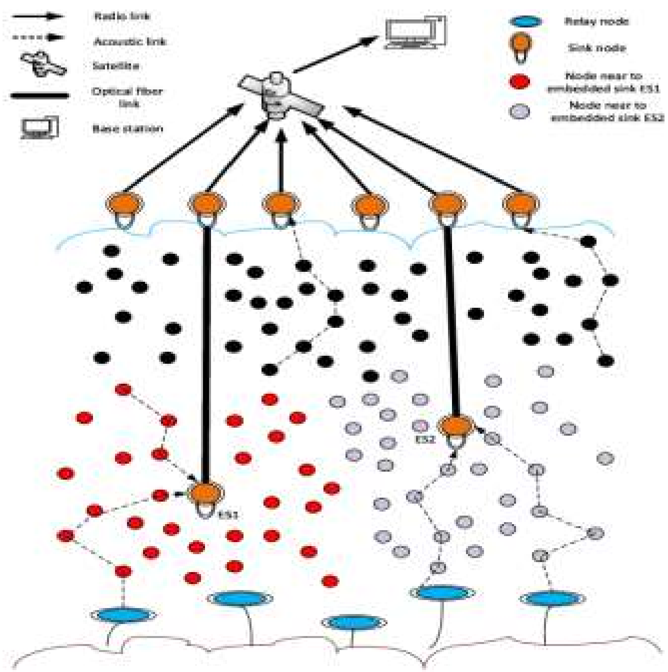


Figure 2-18: Network Topology with Two Embedded Sinks [84]

PCR Protocol

Recently, a novel Power Control-based opportunistic Routing (PCR) protocol for Internet of Underwater Things (IoUTs) was proposed in [85]. To achieve energy-efficient data delivery in IoUTs, the authors designed an opportunistic routing protocol that includes transmission power control. In PCR, each node considers more than one transmission power level to choose its candidate set for each next-hop. The protocol process can be divided into three phases:

The first phase is neighbor discovery, where the PCR protocol transmits a periodic beacon for each available transmission power level, to update the neighbors table based on the transmission power level required to reach a neighbor.

The second phase is the candidates relay nodes selection phase. In this phase, a set of neighboring nodes with positive packet advancement will be added to the candidate set. Afterwards, the energy waste for each candidate set is calculated by Equation 2-13 to determine the appropriate transmission power level and the next-hop forwarding set.

$$E_w = (N_u - 1)\left(p_t^k \frac{L}{B} + \left|N_t^{p_t^k}\right| p_r \frac{L}{B}\right) \qquad 2\text{-}13$$

Where N_u is the estimated number of transmissions for successfully delivery of the data packet from node n_i to its next-hop forwarder nodes in the candidate set, B is the data rate, L is the packet size, p_t^k is the transmission power level, $N_t^{p_t^k}$ is the expected transmission count at transmission power level p_t^k and p_r is the reception power level.

Hence, the set of candidate nodes with the least energy waste is chosen as the best candidate set to continue forwarding the packet to the next hop until the packet reaches the destination. The nodes in the candidate set then will be sorted based on their normalized packet advancement to define each node's priority.

The third phase is the Candidates' transmission coordination procedure where PCR applies a timer-based approach to manage the transmission coordination between the candidate nodes. Hence, the higher the candidate node's priority, the lower its packet holding time. Moreover, any low priority candidate node will cancel its transmission if it hears the packet transmission from a higher priority candidate node. In the PCR protocol, the packet delivery ratio is increased by modifying the transmission power level at each hop, in order to choose the appropriate candidate node set from the sender neighbors to continue forwarding the data packets to reach the sink(s) on the water surface. PCR also reduces the transmission power level at a node in dense networks to reduce the number of retransmissions, which decreases the energy consumption in some cases. However, as we can see from the results presented, the energy consumption is greater than that in the compared related works, which will affect the network lifetime.

2.5 Summary Comparison of OR Protocols for UWSNs

The general comparison of OR protocols for UWSNs based on the protocol's characteristics and features is summarised in the Table 2-1 below.

Table 2-1: General Comparison of OR protocols for UWSNs

Protocol	Category	Sender-side / Receiver-side	Sink(s)	Requirements	Knowledge required/ maintained	Advantage	Disadvantage
DBR [18]	Pressure-based routing	Receiver-side	Multi-sink	Nodes with special H/W	The depth information of sending packet nodes	• Uses depth threshold for controlling the number of forwarding nodes and save some energy. • Achieves high packet delivery ratio.	• High energy consumption. • Duplicated packets are increased with an increase in the number of deployed nodes.
HydroCast [74]	Pressure-based routing	Sender-side	Multi-sink	Nodes with special H/W	Two-hop connectivity and the pairwise distances for the neighboring nodes	• Reduces end-to-end delay. • High delivery ratio. • Void handling technique by using recovery path.	• High energy consumption due to repeating the process of finding detour path. • High overhead due to requiring two hop neighboring node information.
EEDBR [19]	Pressure-based routing	Sender-side	Multi-sink	Nodes with special H/W	The depth and the residual energy information of neighboring nodes having smaller depth	• Utilizes the energy balancing of the nodes in turn to expand the network lifetime. • Number of forwarding nodes is controlled based on both the depth and the residual energy of the sensor nodes.	• Node resources are rapidly consumed due to periodically broadcasting depth and residual energy of neighboring nodes. • Void area issue. • High network overhead due to periodically broadcasting for neighboring node information.
VAPR [75]	Geography-based routing	Sender-side	Multi-sink	SEA Swarm nodes	Next-hop direction and hop distance information at each node	• Reduces end-to- end delay. • Void handling technique uses directional opportunistic data forwarding algorithm. • Uses multi-sink, which reduces the sensor node's battery drain and high traffic.	• High energy consumption because it uses enhancing and measuring the distance to the neighbouring nodes and broadcasts the measured information. • Holding up to two hops neighbors' information to bypass the void area can impose high overhead to the network.

Protocol	Category	Sender-side / Receiver-side	Sink(s)	Requirements	Knowledge required/ maintained	Advantage	Disadvantage
IVAR [76]	Pressure-based routing	Receiver-side	Single-sink FIXED	Relay nodes and anchored nodes	Own depth, one-hop neighbors and sink location	• Eliminates all the routes leading to a void area and therefore no need for switch to recovery mode. • Number of relay nodes decreases with increasing the network density.	• A hidden node problem causes a redundant packet transmission. • An extra amount of energy consumed due to the redundant packet transmissions.
WDFAD-DBR [77]	Pressure-based routing	Receiver-side	Multi-sinks	Anchored, relay and sink nodes.	Own depth, one-hop neighbor's information and two-hop neighbor's depth.	• Duplicated packets handled by dividing the forwarding area and neighbor node prediction mechanism, which helps to reduce the energy consumption. • Sticking in void holes is reduced by using the depth of expected next hop.	• Periodic control packets and ACKs consume the node's resources. • Retransmission is required if the best forwarding node failed to transmit the packet. • Choosing a fixed primary forwarding area might affect the flexibility of routing. • The void area is not handled since the trapped nodes are not eliminated from the forwarding set.
GEDAR [78]	Geography-based routing	Sender-side	Multi-sink	Nodes with special H/W	Position information of its own neighbours and sink	• Network topology control technique increases the connectivity of the network. • Reduces the number of packet retransmissions. • Void handling technique uses a network topology control method.	• High physical energy consumption due to nodes movement to adjust their depth. • Ignores sensor node energy level when selecting the forwarder node with high physical energy consumption, which may lead the protocol to be unable to select forwarding node after a period of time due to exhausting their energy in physical movement.

Protocol	Category	Sender-side / Receiver-side	Sink(s)	Requirements	Knowledge required/ maintained	Advantage	Disadvantage
FLCOR [79]	Pressure-based routing	Sender-side	Single-sink	Nodes with special H/W	energy consumption ratio, packet delivery probability from the source node to the neighboring relay node	• Reduces the duplicate packet transmission. • The fuzzy logic approach saves node energy and reduces collisions.	• Need to apply the fuzzy logic again to select the second forwarding node if the first one failed to transmit the packet. • Does not consider the multi-sink architecture. • Does not handle the void area. • distributed beaconing cause in extra amount of consumed energy
VHGOR [80]	Geography-based routing	Sender-side	Single-sink	Geo. location is available	Own location/ neighboring table	• Void node handled in two ways (i) Convex void handling and (ii) Concave void handling (or) recovery mode.	• Consumes restricted resources (memory through maintaining neighbouring table and energy through node beacons).
EECOR [81]	Pressure-based routing	Sender-side	Single-sink	Nodes with special H/W	The depth information of the sensor nodes and their current residual energy	• Fuzzy-based best node forwarding selection. • High packet delivery ratio. • Consumes less amount of energy and extends the network lifetime.	• Does not consider the multi-sink architecture. • Repeating the fuzzy approach each time to choose the best forwarder drains the source resources. • Suffers from void areas. • Updating the energy information is required for routing.
EVA-DBR [82]	Pressure-based routing	Sender-side	Multi-sinks	Anchored, relay and sink nodes.	Own depth, one-hop neighbor's information and two-hop neighbor's depth.	• By resizing the forwarding area the hidden problem is addressed in some cases. • A trade-off between the energy consumption and latency based on the predefined maximum delay. • Detects the void and trapped nodes before the data packet gets stuck in a void node.	• Periodically broadcasting neighbor's information consumes the node's resources. • Duplicated packet transmissions in sparse network. • Hidden problem may appear if the forwarding range is chosen to be more than half of the transmission range.

Protocol	Category	Sender-side / Receiver-side	Sink(s)	Requirements	Knowledge required/ maintained	Advantage	Disadvantage
EDOVE [83]	Pressure-based routing	Receiver-side	Multi-sink	Anchored, relay and sink nodes.	Own depth, one-hop neighbor's information and two-hop neighbor's depth.	• Considers energy level as one of its parameters, which helps to reduce energy consumption and avoid energy holes.	• Exchanging the neighbour's info and maintaining the neighbour's table consumes the node's resources. • Duplicated packet transmissions increase the consumed energy. • The void area is not handled completely since the protocol only addresses energy void holes.
EBER[2] [84]	Pressure-based routing	Sender-side	Multi-sink	Anchored, relay and underwater sink nodes.	Two-hop Potential Forwarding nodes.	• Residual energy of the nodes is used to reduce the duplicated packets and decreases the energy consumption. • Transmission energy adaptability supports reducing the void holes. • Embedded sinks used to increase the packet delivery ratio.	• Suffers from large end-to-end delay as well as accumulative Propagation Distance. • Communication between embedded sinks and on-surface sinks is costly. • Duplicate packets sent to surface due to node's control power mechanism near the sinks
PCR [85]	Geography-based routing	Sender-side	Multi-sink	Nodes with power control mechanism.	Position information of its own, neighbours and sinks	• Joint design of OR and power control improves the link quality at each hop. • Reduces the number of packet transmissions in dense networks by reducing the transmission power level. • Void handling technique exploits a power control mechanism.	• Power control mechanism consumes more energy in forwarding set selection phase, which causes high-energy consumption overall. • Communication overhead due to broadcasting the beacon messages with different power levels.

Table 2-1 classifies the protocols as to sender-side or receiver-side. The decision for forming the next hop forwarding set depends on the sender/receiver-side.

Sender-side protocols require larger communication overhead as sensors need to update their neighbor tables regularly by exchanging node information. This results in expending the node's limited resources (i.e. battery and memory).

For receiver-side protocols, the sender does not have any information about its neighbors and does not know its forwarding set. This can cause a large number of duplicate transmissions and increase the chance of transmission collisions requiring retransmissions. This can result in packet loss and sensor nodes can consume valuable amounts of their energy decreasing overall network stability period.

Most of the reviewed protocols were proposed to improve the network performance and deliver data packets successfully by addressing the void area problem using different void area handling techniques; however, they still suffer from the trapped nodes problem, which need more attention. Table 2-1 also indicates the network topology requirements (i.e. special type of nodes, nodes with special hardware and types of nodes implemented in the topology), and special information required or needed to be maintained during the data packet routing. Moreover, the advantages and drawbacks of each protocol were listed in the last two columns of Table 2-1.

To the best of our knowledge, our proposal protocols are the first OR that follow the hybrid candidate set selection category. In contrast with the reviewed protocols, which use periodic beacons message that cause communication overhead and consumes nodes resources, the short packets used to exchange the node's information are less likely to be lost, this can reduce the number of transmissions, conserve node energy and helps in an enhancement in the candidate coordination performance. Moreover, the majority of the existing protocols handled the void area by switching forwarding technique to the recovery mechanism and most of them suffer from the trapped node problem. The only protocol that handles the void area problem and identifies all void/trapped node is the IVAR protocol. However, IVAR is a unicast protocol which utilizes the periodic beaconing broadcasted by the sink and relay so, sensor nodes can obtain reachability information. The beacon interval has great impact on the network performance. The protocol still suffers from duplicate transmissions due to prioritizing mechanism, which relay on the depth that may will be same for more than one node, and the holding time, which relay on common parameters between more nodes. These limitations were addressed through the novel hop-count discovery mechanism and the prioritizing technique.

2.6 Conclusion

In this chapter, we presented an overview of the UWSNs, underwater sensor nodes platforms, various types of UWSNs architectures, UWSNs applications and basics of the acoustic communication channel. We also presented an overview of UWSNs routing protocols, the current challenges facing the routing protocols designers and the concept of OR including OR construction blocks and OR protocols classification. Then, a survey of the OR protocols in UWSNs was reported, which includes the existing geographic-based and pressure-based OR protocols. Finally, a summary comparison of these existing protocols consisting of protocols characteristics, requirements, benefits and drawbacks was provided.

Chapter 3 Energy Efficient Depth-based Opportunistic Routing Protocol

3.1 Overview

In this chapter, we introduce a novel routing protocol called an Energy Efficient Depth-Based Opportunistic Routing protocol (EEDOR). Our core contribution in this chapter is offering a new proposal for a competitive OR protocols in UWSNs in order to conserve node's limited energy and extend the network stability period. The technique utilized by EEDOR (i.e. depth difference and priority ranking) avoids packet collisions since all candidate nodes, including those at the same depth, have different holding times. In addition, in EEDOR, redundant transmissions caused by holding time expiration are less likely since the lower priority node have enough time to hear the higher priority node transmission and suppress its transmission. We implement EEDOR using an OR approach, where a source node and its neighbors can exchange their information to form the forwarding set by utilizing wireless broadcast [17]. Our work was motivated by a number of considerations. Due to sensor node tasks and the harsh underwater environment, sensor nodes can exhaust their energy decreasing the UWSN lifespan. Besides, underwater acoustic channel characteristics and limitations make the network vulnerable to congestion caused by packet collisions. In addition, the fading of underwater acoustic signals affects the performance of routing protocols. Under the acoustic channel conditions, reducing the number of packet duplications and retransmissions is critical task for not just reducing congestion but also reducing energy usage.

The main contributions of our work (EEDOR) in the area of routing protocols for UWSNs are:

1. A new routing protocol for UWSNs is modeled that integrates OR technique with greedy mechanism for efficient energy consumption.

2. A novel holding time formula is introduced that incorporates both the priority of the candidate node and the depth difference between the packet sender and each candidate node of its forwarding set.

3. Arithmetic progression is utilized to calculate the priority value of candidate nodes in the forwarding set. The suggested technique increases the priority value arithmetically for a minor change in forwarder depth. As a result, the higher depth candidate nodes can suppress their transmission successfully.

4. The stability period of UWSNs is improved through saving nodes resources by controlling the number of forwarding nodes to reduce the duplicated transmissions. Extensive simulation results using MATLAB demonstrate that the EEDOR protocol outperforms the comparative existing protocols.

The rest of this chapter is organized as follows. In Section 3.2 we list the system assumptions and describe the system model. Section 3.3 describes the proposed protocol EEDOR. Performance setting and evaluation analyses are presented in Section 3.4. Finally, Section 3.5 concludes the chapter.

3.2 System Assumptions and System Model

3.2.1 System Assumptions

The following characteristics are assumed for the UWSNs system model:

1. Sensor nodes are distributed randomly in a three-dimensional underwater network field following 3D UWSNs architecture.
2. Sensor nodes are assumed to be static and the location of all the nodes will not change once they are distributed.
3. All underwater sensor nodes are homogeneous in terms of energy, communication and processing capabilities.
4. Underwater sensor nodes are depth-aware; that is, they are equipped with depth a sensor.
5. The deployed sensor nodes use fixed transmission power level and receiving power level. In addition, each node has a fixed transmission range of R_{tx}.
6. Underwater sensor nodes are equipped with an acoustic modem to communicate with each other and/or with the sinks.
7. The sinks are equipped with both radio modems to communicate with each other and/or with a base station, and acoustic modems to communicate with the underwater sensor nodes.

3.2.2 System Model

Our proposed protocol is an OR protocol that follows the hybrid forwarder set selection category as classified in [1]. Our proposed network architecture, illustrated in Figure 3-1, consists of a number of sensor nodes randomly deployed at different depth levels in the underwater area of interest and multiple stationary sinks situated randomly on the water surface. The nodes in Figure 3-1 are divided into six types of nodes:

- Source nodes are the nodes that monitor and sense the underwater physical phenomena; they are responsible for collecting data related to an event and transmit it to the next forwarders. We later refer to source nodes as packet holder (P_{holder}) nodes.

- The next forwarder nodes are the nodes in the forwarding set that have the highest priority to transmit the packets received from source node. Consequently, they are the source nodes for the next hops.

- The forwarder candidates are the nodes in the forwarding set that have lower priority value and they hold the packet for period of time; they suppress their transmission and drop the packet if they hear a higher priority node transmission. In this case, they will not be source nodes.

- Neighbor nodes are the nodes within the transmission range of the P_{holder} but their depth is greater than the P_{holder} depth. These nodes do not participate in the data packet transmission since they receive the packets from superior node closer to the surface.

- The idle nodes are those nodes that are not part of a given source to sink transmission. These nodes did not receive any data packet from any P_{holder} nodes as they are apart from their communication range.

- Sink(s) are located on the water surface to collect the data from the underwater sensor nodes process and store it or send it to the off-shore stations for processing and analysis. Sinks can communicate via radio modems to each other and/or with other off-shore stations, and via acoustic modems to communicate with the underwater sensor nodes.

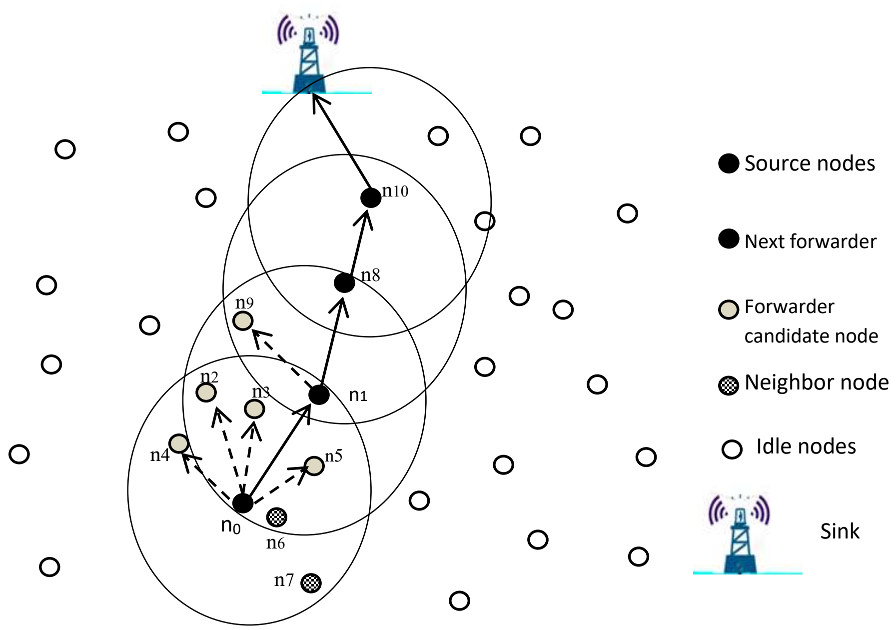


Figure 3-1: 3D-UWSNs Architecture

3.3 The EEDOR Routing Protocol Overview

It is well known that in wireless networks, sensor nodes expend more energy in transmitting data packets than in receiving them. Therefore, reducing the number of transmissions and forwarded packets can noticeably decrease the rate of energy consumption, preserving resources and prolonging the network lifetime. The designers of UWSN protocols considered a variety of underwater factors to address various issues. Enhancing the lifespan of the UWSNs by saving node energy is an essential objective since replacing and/or charging underwater node batteries is a costly and challenging task in the hostile underwater environment. Many researchers have expressed interest in this topic. In this section, we present the proposed EEDOR protocol that considers the depth difference between two nodes and the ordered list of forwarding candidates to reduce redundant transmissions and collisions in order to decrease the energy consumption and extend the network stability period.

3.3.1 Basic Idea of EEDOR

The EEDOR protocol we propose is a greedy routing protocol where in each step, each P_{holder} (source or next forwarder) node forwards the data packets upward to the neighbor node that makes the greatest positive progress to reduce the distance to the water surface where the sinks are deployed. The EEDOR protocol is broken down into rounds, each one including a set of procedures to achieve the protocol goal by delivering the data packet to one of the sinks. Moreover, EEDOR utilizes OR, therefore a subset of the neighbors will form the selected forwarding set to carry on forwarding the data packet to reach its destination. This greedy OR routing technique used by EEDOR can be done in two stages: forwarding set formation and data packet forwarding. These EEDOR process stages can be clarified with a simple example as illustrated in Figure 3-1 where the path of a data packet from the source node n_0 to the nearest sink, s_2 is established as shown in the following steps:

1. n_0 broadcasts its local information (ID, depth) to select its forwarding set.

2. Nodes n_1, n_2, n_3, n_4, n_5, n_6, and n_7 are within n_0 transmission range and they receive n_0 information.

3. Nodes n_1, n_2, n_3, n_4, n_5 will respond to the message from n_0 with their depth and ID. While nodes n_6, and n_7 will not respond to n_0's message since they have a greater depth than n_0.

4. Node n_0 transmits the sorted ID list along with the data packet. In EEDOR, the Rank value is given based on node depth such that the sorted list is n_1, n_2, n_3, n_4, n_5. The nodes n_1 and n_2 have the same depth but different ranks since each node have unique indices in the sorted list.

5. Node n_1 will have a rank (i.e. the position of the node's ID in the list of candidate nodes IDs) of 1 and therefore a hold time (i.e. the period of time that node can hold the packet before forwarding it) of 0, effectively becoming the next source node.

6. The routing procedure will repeat such that the data packet will hop from n_1 to n_8 to n_{10} (i.e. illustrated by solid arrow in Figure 3-1). As n_{10} is within transmission range of a sink it will reduce its forwarding set to that sink.

3.3.2 Forwarding Set Formation

EEDOR is a hybrid forwarding set selection procedure as defined in subsection 2.3.1 referring to [1] in which the current forwarder node and its neighbors choose the forwarding set collaboratively. In the first step of each round, the deployed sensor nodes begin gathering data from the surrounding environment.

In this step, the current source node generates a forward request message (FwdReq) contains its local information (ID, depth) and transmits it to its one hop neighbors. The FwdReq message format is shown in Figure 3-2.

Source ID	Source depth	Sequence number

Figure 3-2: Forward Request Message Format

Each neighbor node receives the FwdReq message and compares its own depth with the depth of the source in the received FwdReq message. Only nodes with a lesser depth will reply with a forward reply message (FwdRep) that has the same format as the FwdReq message and contains the neighbor local information (i.e. neighbor ID and depth). And if a sink sends a FwdRep then the source reduces the forwarding set to this sink alone and transmits the data packet directly through one hop to that sink.

Figure 3-3 illustrates the forwarding set selection procedure in our proposed protocol. This procedure is done by the source then it is repeated by each P_{holder} until the data packet reaches one of the sinks. After the first transmission, the nodes that will continue forwarding the data packet and repeat the above forwarding set selection procedure are called P_{holder} since they are not the data packet generator.

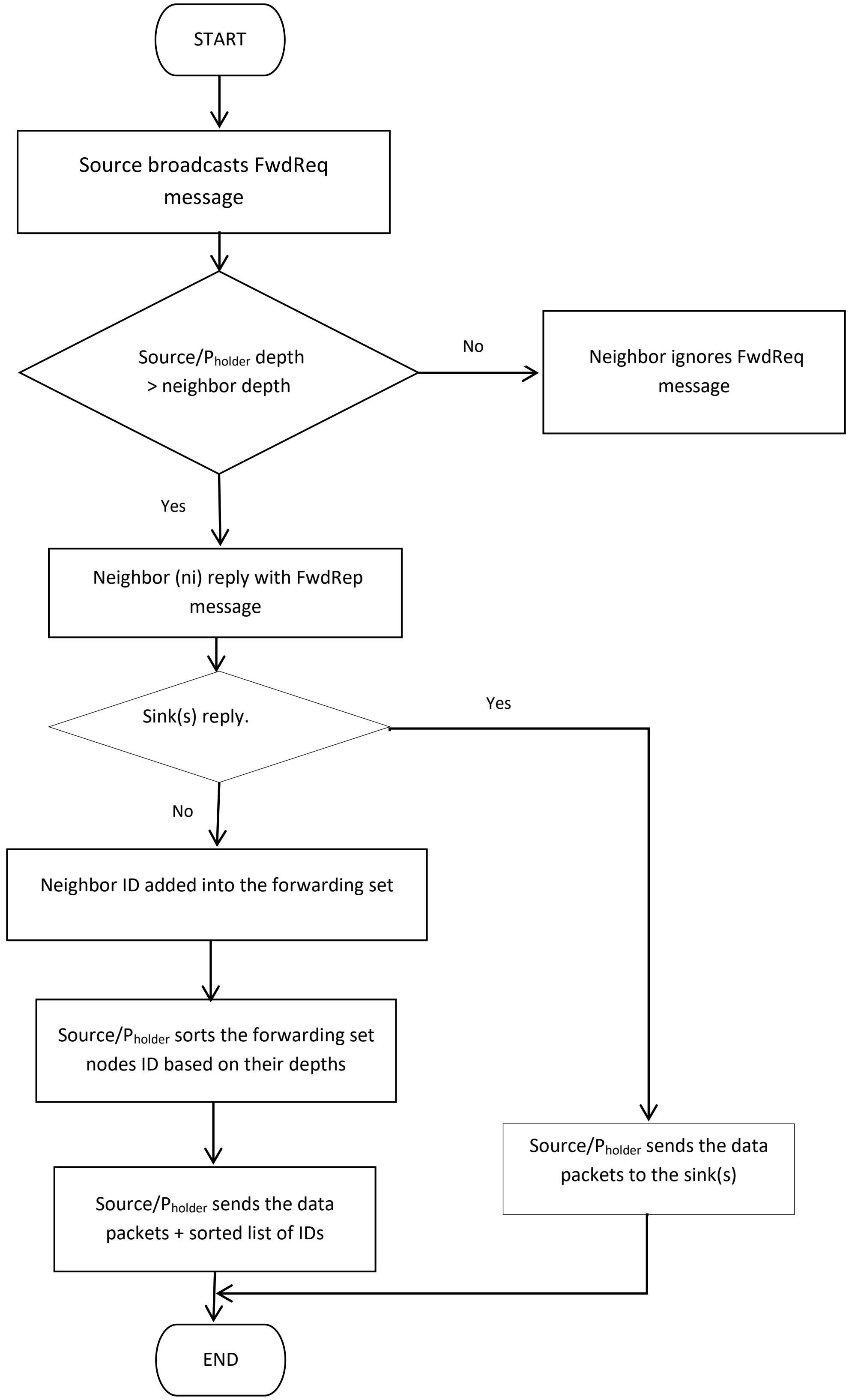


Figure 3-3: Forwarding Set Selection Process

3.3.3 Data Packet Forwarding

Once a P_{holder} has a packet to transmit, its neighbors and itself will exchange their local information as explained in the previous subsection. As soon as the P_{holder} receives information from qualified nodes (those nodes respond with an FwdRep messages), it sorts their IDs in a list based on their depth difference. This sorted list will be attached to the header of the data packet to control the packet forwarding through prioritizing the forwarding nodes. The data packet format is illustrated in Figure 3-4.

The Data packet format required for the EEDOR is simple; it consists of only the list of qualified nodes IDs with no other information as a field for controlling the cooperative process between the candidate nodes, the packet sequence number to identify each data packets and the packet payload.

List of qualified nodes IDs	Packet sequence number	Packet Payload

Figure 3-4: Data Packet Format

When the qualified nodes receive the data packet, they start computing their holding time. The most appropriate node will have a 0 as its holding time value and will carry out its forwarding set selection procedure and transmit the data packet provided its forwarding set is not empty. If the most appropriate node successfully forwards the packet, the other candidate nodes in the forwarding set will drop the packet if they are in the transmission range of that most appropriate node and they heard the packet transmission before their holding time expired. If not, the next node in the sorted list will transmit the data packet, and so on. These steps will be repeated until the packet reaches the sink or all the candidate nodes in the forwarding set fail.

3.3.4 Holding Time Calculation

As the underwater nodes are deployed randomly, more than one of these deployed nodes could have the same depth and/or distance from the sinks or the P_{holder} node. The number of these nodes, which have the same depths and/or the same distance from the sink(s) or the P_{holder}, increases when the number of randomly deployed nodes is increased. Protocols that adopted this criterion (i.e. depth) to calculate holding time, such as DBR, could have several nodes with nearly identical transmission times. This can increase the packet collisions and retransmissions, which can cause excessive network energy consumption and reduce the overall network performance. In our proposed protocol, we address this issue through our novel holding time technique as follows: first, the list of qualified nodes in the selected forwarding set are sorted in descending order based on the difference between the P_{holder} depth and their depth in a list by P_{holder}. Then, when the selected forwarding nodes receive the sorted list, each node will assign itself a rank based on its place in the sorted list. After that, to calculate the holding time (*HT*) in sec. of these candidate nodes we use Equation 3-1 below.

$$HT = \frac{\frac{2 \times R_{tx}}{s}}{D_{diff}} \times (R_{tx} — D_{diff}) \times (Rank — 1) \qquad 3\text{-}1$$

Where R_{tx} is the node's transmission range in m, s is the speed of sound in the underwater environment (1500 m/sec.), D_{diff} in m is the difference between the P_{holder} node and the forwarder node depths, and the *Rank* is the node's position in the sorted forwarding set list, attached with the data packet. The ID of the candidate node that has the greatest depth difference is located at the top of the forwarding set list, which gives it a rank (*Rank*) of 1. By using the Equation 3-1, the *HT* of this node will be 0, which means that this node will begin its transmission process instantly, whereas other candidate nodes in the selected forwarding set will wait for an assorted period of time based on their rank values before they start the transmission process. Utilizing the parameter *Rank* ensures that all candidate nodes of the forwarding set, even ones with similar depths, will have distinct holding times, which prevents transmission collisions. Using node depth difference, D_{diff}, in the first term of the holding time formula, Equation 3-1, assigns nodes closer to the P_{holder} a longer holding time, thereby making short hops between nodes less frequent. In contrast to our proposed EEDOR protocol, DBR uses $\delta = R_{tx}$ in the first term of their holding time formula, Equation 2-9, which assign the same value for this term for all forwarding candidates and that results in a significant convergence of the holding time for all candidates.

In summary, EEDOR follows a time-based coordination technique [1] where the most appropriate node begins the packet transmission and the remaining candidate nodes will suppress their transmission until their waiting time has expired. They will discard the packet if they hear the best forwarder transmission. This method conserves a substantial amount of node energy.

3.3.5 Acoustic Channel Model

Wireless sensor networks use sensor nodes, which are battery-operated devices. Due to the underwater acoustic communication channel characteristics, the sensor nodes in UWSNs exhaust a substantial amount of their energy. Sensor networks ultimately become unusable as sensor nodes' batteries run out. As in [46, 47, 48], the sonar equation that describes the signal-to-noise ratio (*SNR*) of passive sonar is illustrated mathematically in Equation 3-2 below: The passive sonar equation, which describes the SNR in dB, is the starting point for the acoustic model:

$$SNR = SL - TL - NL + DI \qquad 3\text{-}2$$

Where

SL is the source level that can be calculated mathematically as in [48] using the following Equation, whereas P_{trans} in watts:

$$SL = 170.8 + 10 \times \log P_{trans} \qquad 3\text{-}3$$

TL is the transmission loss, and it can be mathematically found through Equation 2-3, *NL* is the noise level that can be found by Equation 2-5 and $DI = 0$ is directivity index as denoted in [47].

Moreover, as given in [46, 49, 86], the underwater acoustic channel path loss and ambient noise were discussed in subsection 2.2.4. The underwater acoustic micro-modem [21, 48, 72] is assumed to utilize binary phase shift keying (BPSK) modulation. As a result, in an underwater Rayleigh fading channel, the bit error rate (BER) of BPSK may be computed as [48]:

$$P_e = \frac{1}{2} \times \left(1 - \sqrt{\frac{10^{SNR/10}}{1+10^{SNR/10}}}\right) \qquad 3\text{-}4$$

As a result, referring to the delivery probability of a packet with size L bits for every pair of nodes separated by distance d is simply given by:

$$P = (1 - P_e)^L \qquad 3\text{-}5$$

Note that, in the acoustic channel model, the noise level (influenced by shipping activity and wind speed) and the transmission loss (influenced by spreading factor, distance and the absorption coefficient, which is a frequency dependent) can affect the SNR value, which as a result has an effect on the packet delivery probability. This impact on SNR and the probability of a packet delivery for various values of wind and shipping noise at power transmission level $P_{trans} = 2$ watts and distance from 0 to 2000 m are illustrated in subfigures a) and b) in Figure 3-5 respectively.

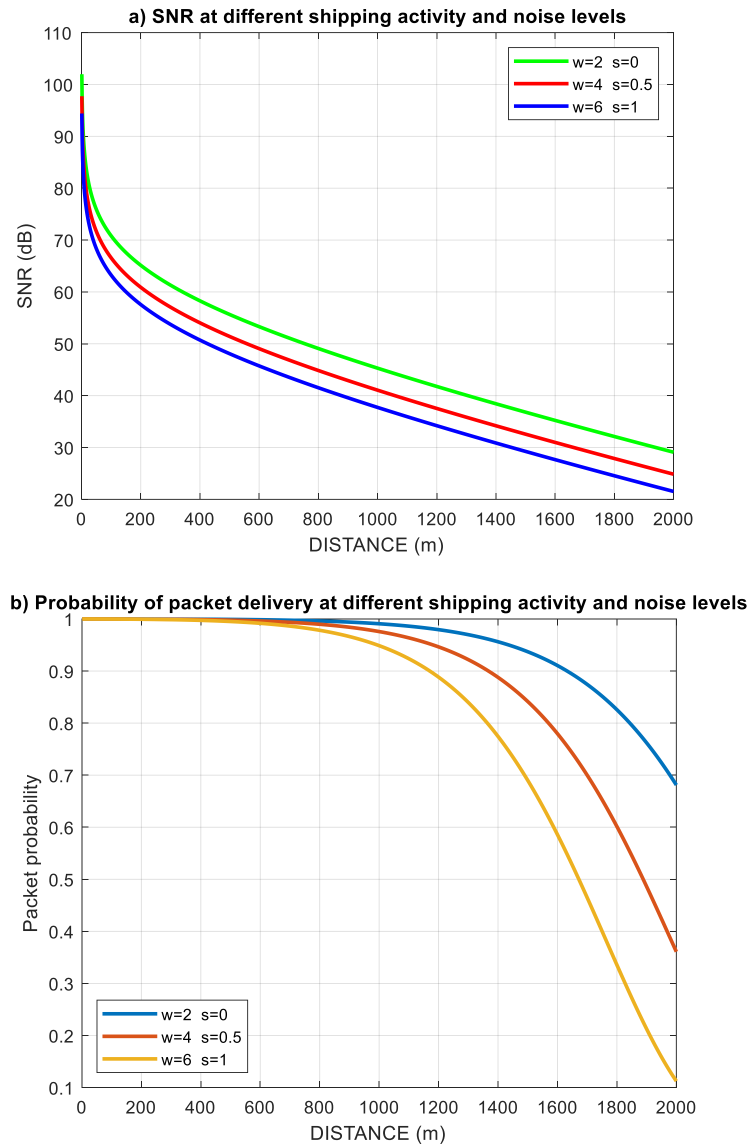


Figure 3-5: Impact of shipping activity and noise level on a) SNR and b) probability of packet delivery

3.4 Performance Setting and Evaluation

This section provides experiments and performance evaluation results of the proposed EEDOR protocol. The EEDOR protocol selects forwarding nodes in an energy-efficient manner while also balancing energy usage across the network. Because conserving energy is the main motivation, primary performance metrics including mean energy consumption per node, number of transmission and packet delivery as functions of the number of nodes in the network, and network stability period (network lifetime), are of specific concern. The novel waiting time proposed, as computed in Equation 3-1, controls the coordinated transmissions process since it allows nodes with larger rank values than the source to overhear the packet transmission and discard their packet.

3.4.1 Basic Simulation Parameters

We analyze the performance of our proposed EEDOR protocol for UWSNs and the comparative protocols via simulation conducted in MATLAB. The communication specifications we use are identical to those of a commercial acoustic modem, LinkQuest UWM1000 [87]; the power consumption by nodes in transmitting, receiving, and idle mode are 2, 0.1, and 0.01 watts, respectively. Other general parameters we used in our simulation are listed in Table 3-1. Moreover, the depth threshold for DBR is set to 0 as initialized in the related study [18] we use in our comparison. EEDOR network operation progresses in runs. In each simulation run, a source node is chosen at random among all the randomly distributed nodes and all the packets are directed upward to be delivered to one of the five sinks on the water surface. The statistical data provided in this chapter were obtained after running our simulation for 100 runs.

Table 3-1: Simulation parameters

Parameters	Value
Network size	$500m \times 500m \times 500m$
Number of sinks	5
Number of nodes	200 – 800
Maximum transmission range	100m
Distribution	Random
Initial Energy	70 J
Data packet size	50 bytes
Data rate	10^4 bps
Frequency	25 kHz

3.4.2 Evaluation Results and Analysis

To assess the effectiveness of our proposed protocol performance we compare the EEDOR protocol with the well-known DBR [18] and EEDBR [19] routing protocols, considering the following energy conservation performance metrics.

A. Energy Consumption:

In our simulation of the DBR and EEDBR protocols, and our proposed EEDOR protocol, the total energy consumption for all the nodes is calculated. The total energy consumed (E_{total}) in J, can be derived from the forwarding set selection energy (E_{fwd}), the data packet forwarding energy (E_{trans}), and idles state energy (E_{idle}). Note that we did not consider the energy consumption due to computation at each node. Hence, the overall energy consumption of the network can be calculated mathematically as

$$E_{total} = E_{fwd} + E_{trans} + E_{idle} \quad \text{3-6}$$

Where E_{fwd} in J is the energy expended in transmiting and receiving FwdReqs and FwdReps, E_{trans} in J is the energy spent in transmiting and receiving the data packets, and E_{idle} in J is the energy spent in the node's idle listening state [18].

The value of E_{fwd} for transmitting and receiving each FwdReq/FwrdRep message can be calculated using the value of transmitting and receiving power in watts P_{trans} and P_{recv} respectively, multiplied by the FwdReq/FwdRep message size (L_{size}) in bits, over the data rate (D_P) in bits/sec..

$$E_{fwd} = P_{trans} \times \frac{L_{size}}{D_P} + P_{recv} \times \frac{L_{size}}{D_P} \quad \text{3-7}$$

The same concept is used for calculating the E_{trans} *and* E_{idle} with modifying L to denote the data packet size when computing the E_{trans} and L_{size} set as 1 when computing E_{idle}.

The overall trend for the two existing protocols is an increase in the overall energy consumption as the density of network increases as shown in Figure 3-6. This increase does not occur with EEDOR because network density has a negligible effect on our forwarding method, resulting in almost constant energy consumption as network density increases. As a result, our EEDOR protocol outperforms both the DBR and the EEDBR protocols. We can also observe that the difference in overall energy usage between the three protocols, particularly between DBR and the other two, EEDBR and EEDOR, grows quickly when increasing the node density. The large difference in energy consumption between the comparative protocols as the network density increases is most likely driven by an increase in the size of the forwarding set and redundant transmissions in DBR as the network density increases. However, EEDBR controls the number of duplicated transmissions but not as well as EEDOR.

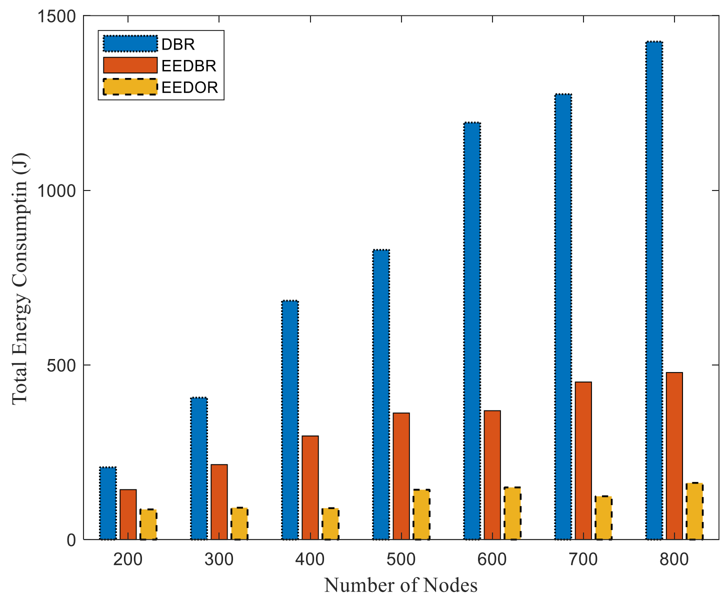


Figure 3-6: Total Energy Consumption

To prove the significance of the EEDOR protocol, the confidence interval (CI) of the error bars is also used. In our experiments, a 95% CI is chosen to test the mean energy consumption per node to verify the protocol's significant. As demonstrated in Figure 3-7, the mean energy usage per node for the proposed EEDOR protocol is much lower than the mean energy for the other two comparative protocols (DBR and EEDBR). The 95% CI error bars in Figure 3-7 indicate that our EEDOR protocol has the lowest error range, particularly for the topologies have high node densities. This narrow error bar range for mean energy consumption means the node energy consumption is more balanced for EEDOR than the other two protocols. Besides the absence of overlap between the error bars for the three protocols indicates that the energy spent by the comparitive protocols are different and as showen in Figure 3-7 EEDOR protocol exhausts less energy than the other two protocols. DBR lacks any energy balancing techniques; therefore, it has a wide range in mean energy consumption per node, as illustrated by the error bars in Figure 3-7. Conversely, EEDBR balances energy usage by selecting a forwarding set that takes residual energy into account. However, due to collisions, certain nodes in the EEDBR retransmit more frequently than others. These side effects are avoided through EEDOR process.

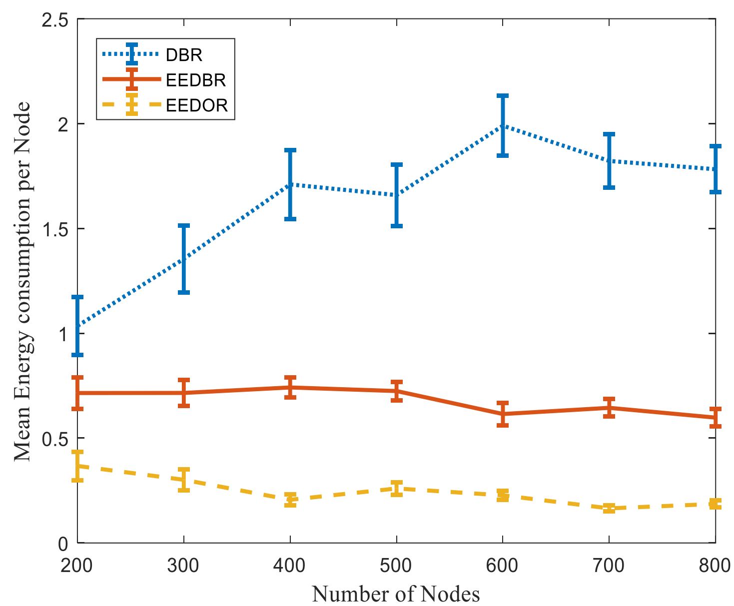


Figure 3-7: Mean Energy Consumption per Node

EECOR [81] is another OR protocol that uses a single sink architure rather than multiple sinks used in EEDOR. According to the results demonstrated by the authors of [81], the EECOR improves average energy usage over DBR by roughly 40% for sparse networks (200 nodes) and 14% for dense networks (700 nodes). In contrast, our EEDOR protocol demonstrates an improvement over DBR ranging from approximately 64% for sparse networks to 90% for dense networks. We conclude that our EEDOR protocol outperforms EECOR in average energy consumption.

B. *Total Number of Transmissions:*

To study the reason behind the large difference in total used energy, particularly in the networks with high node density, between existing efforts (i.e. DBR and EEDBR) and the proposed EEDOR, we computed the total number of data packet transmissions for all three protocols through the 100 runs. Figure 3-8 depicts how the number of transmissions in EEDOR is almost constant in different network densities and is much less than the other two protocols. Moreover, the figure demonstrates that DBR and EEDBR are close to each other in sparse network topologies but diverge as network density increases. Besides, for DBR and EEDBR the number of transmissions increases rapidly with network density.

The DBR protocol adopts a flooding technique to deliver the data packet to the destination; this flooding technique increases the number of transmission nodes as the network density increases. EEDBR utilizes residual energy and depth for forwarding set selection and implements routing paths to deliver data packets. This routing technique does not utilize the shortest paths, which means more nodes will transmit, resulting in additional transmissions.

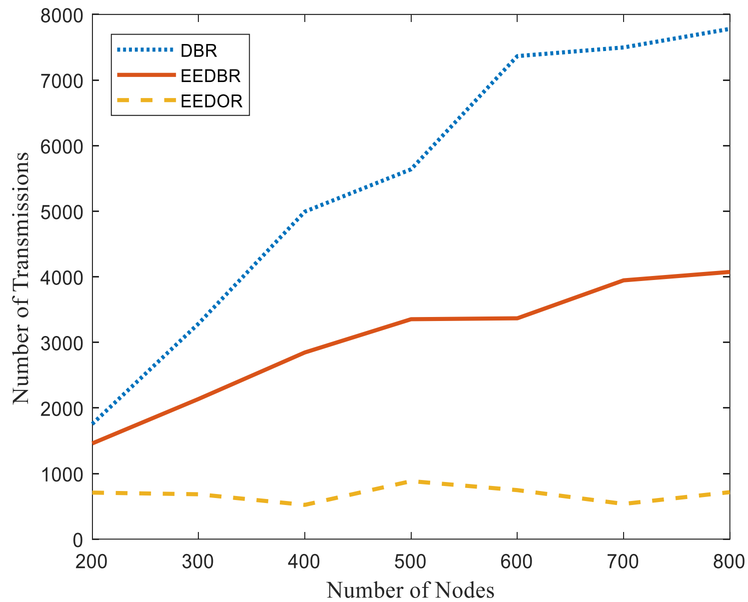


Figure 3-8: Number of Transmissions

On the other hand, EEDOR selects the forwarding nodes such that they create the shortest path from the source to the destination, which means fewer nodes will participate in the forwarding process, resulting in a considerably lower number of transmissions than the other two protocols.

C. *Stability Period of The Network:*

The most common and valuable technique used in wireless sensor network to define the stability period (known also as the network lifetime) of the network is the metric of The First Node Death (FND). The FND represents an estimated value for the round number when the first sensor node loses its communication with other nodes due to expending its energy [88, 89, 90]. To investigate the stability period of the EEDOR protocol vs. the DBR and EEDBR protocols, the scenario setup comprising 200 nodes is assessed since the number of nodes in the forwarding set and the total energy consumption are expected to be similar in all three protocols for this number of nodes.

Our experimental results are shown in Table 3-2, Table 3-3 and Figure 3-9. Table 3-2 displays FND, which represents the round number when the first node in the network runs out of energy.

Table 3-2: FND Round Number

PROTOCOL	DBR	EEDBR	EEDOR
# **Rounds to FND**	1482	2112	3192

We calculated the percentage of the performance results of our proposed EEDOR protocol over the performance results of the previous protocols and the protocol improvement is presented in Table 3-3.

As can be seen from Table 3-3 the EEDOR network lifetime is 53.6% more than the DBR network lifetime and 33.8% more than that of EEDBR.

Table 3-3: Lifetime Improvement

PROTOCOL	DBR vs. EEDOR	EEDBR vs. EEDOR
Difference in rounds to FND	1710	1080
Improvement	53.6%	33.8%

These results are confirmed by Figure 3-9, which illustrates that EEDOR has a longer network lifetime than DBR and EEDBR. Furthermore, from the results presented in [79], we estimate that the FLCOR network lifetime is about 12.5% longer than that of DBR. Since our EEDOR protocol-based network lifetime is 53.6% longer than that of DBR, we conclude that the network lifetime of EEDOR is about 41.1% longer than the FLCOR lifetime.

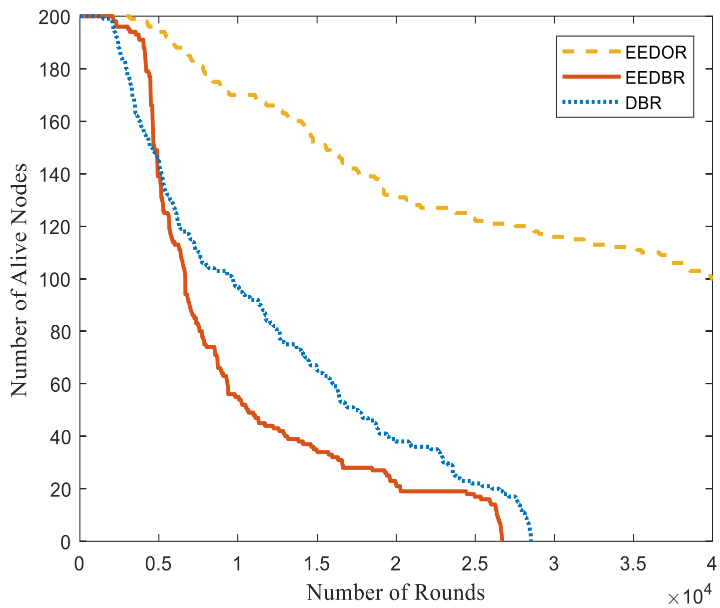


Figure 3-9: Network Lifetime

D. *Packet Delivery Ratio (PDR):*

The PDR tends to rise as the node density increases, as can be seen in Figure 3-10. In other words, because the void holes are more common in sparse networks than in dense networks, the chance of delivering a packet to a sink is lower in sparse networks than in dense networks. Since DBR simply floods the network with packets and redundant packets travel through multiple routes, DBR has the highest PDR. We should point out that the highest PDR for DBR comes at the cost of a high-energy consumption. On the other hand, EEDOR also has a high PDR while still being energy efficient due to its control over the number of forwarding nodes.

In Figure 3-10, we see that as network density increases, the PDR of the EEDOR approaches the PDR of the DBR, eventually becoming equal at 600 nodes. The PDR of EEDBR is lower than that of the two other protocols as illustrated in Figure 3-10, which might be attributed to the lengthy routes traversed by the packets in EEDBR.

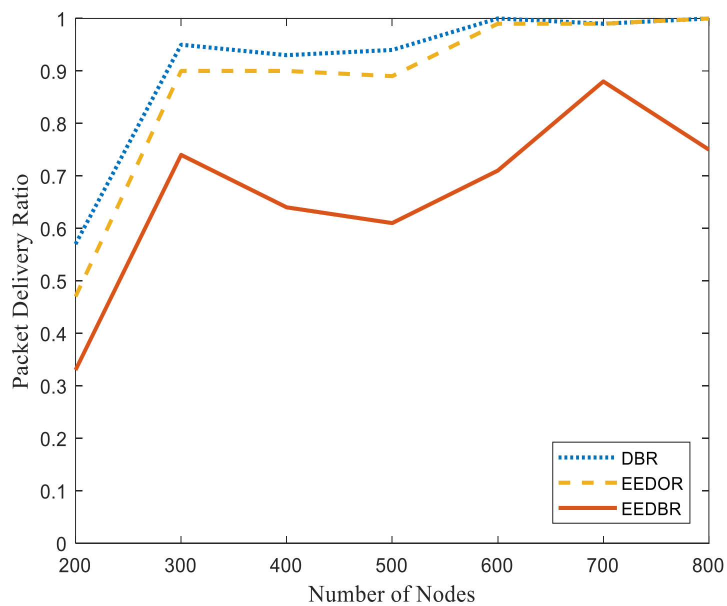


Figure 3-10: Packet Delivery Ratio

3.5 Conclusion

In this chapter, we proposed a novel OR protocol called Energy Efficient Depth-based Opportunistic Routing protocol (EEDOR) for underwater wireless sensor networks. Designing energy efficient routing protocols, which are able to enhance the lifetime of the entire network, is essential for UWSNs. The proposed protocol employs greedy and opportunistic techniques to forward the data packets to one of the randomly deployed sinks through sets of forwarding nodes that collaborate using a new holding time strategy based on their depth and priority to decrease the duplicate transmissions and reduce packet collisions. Our proposed protocol provides useful insights for the future design of routing protocols; it is shown to be an attractive solution especially for network scenarios with higher number of deployed nodes. The numerical results of EEDOR showed better performance than the existing protocols (DBR, EEDBR, EECOR and FLCOR) in terms of overall energy consumption, total number of transmissions, and network lifetime.

Chapter 4 Void Avoidance Opportunistic Routing Protocol for Underwater Wireless Sensor Networks

4.1 Overview

In this chapter, we develop a void avoidance OR routing protocol for UWSNs called EEDOR-VA that increases network performance. The EEDOR-VA protocol excludes all the routes that lead to loss of data packets by detecting all void/trapped nodes and preventing them from being chosen as forwarding candidates and being part of data transmission procedure, thereby saving network resources and delivering data packets at the lowest possible cost (i.e. number of relay nodes, energy, communication overhead, etc.).

The main contributions of our work in the area of routing protocols for UWSNs are listed below:

1- A novel hop-count discovery technique is introduced. The proposed hop-count discovery technique ensures less network communication overhead and lowers network resource depletion.

2- The hop-count discovery mechanism in the proposed protocol eliminates periodic beaconing and its associated costs, widely used in the literature such as [75, 76, 85].

3- The small size of proposed Hop Count Request (HCREQ) and Hop Count Reply (HCREP) messages utilized in the hop-count discovery technique reduces network overhead, collisions and overall energy usage.

4- By reducing duplicate packet forwarding, the forwarding set coordination based on the proposed waiting time assists in decreasing energy usage by reducing the number of transmission nodes.

5- The proposed routing protocol excludes all void/trapped nodes that may lead to a void area in the data routing path. This is accomplished by detecting and removing them from the forwarding set selection procedure using the hop-count discovery technique. Our suggested approach validates node reachability to the sink and updates node hop counts in-route. If a node does not have a route that allows the packet to be sent to the sink(s), the node is removed from the forwarding candidate set.

6- The proposed routing protocol successfully achieves high packet delivery ratio with less node energy depletion. This is done by selecting the shortest routing path.

7- The loop-free multiple opportunistic routing paths determined during the hop-count discovery process enhance the packet delivery ratio.

The remainder of this chapter is organized as follows. In Section 4.2, we describe the void area in UWSNs, and we list the reasons behind void area existence. Section 4.3 describes the network system and assumptions. Section 4.4 describes EEDOR-VA including the protocol phases. Simulation experiments of two scenarios including performance setting and evaluation analyses are presented in Section 4.5. Finally, the conclusion of the chapter is presented in Section 4.6.

4.2 Void Area in UWSNs

Void area is considered as one of the essential issues that can be faced in data transmission specifically in UWSNs. This problem has recently gained the attention of many researchers and a number of protocols were proposed to address the void area problem such as [76, 78, 81, 82, 85]; however, it still needs significant investigation to be completely addressed. To give a clear understanding to void area definition we will follow the same routing protocols classification provided in subsection 2.3.2. In the geographic-based protocols routing protocols, the sensed information is forwarded from the source through the relay nodes with a shorter Euclidean distance to the destination on the water surface. Through this process, if a node holding the sensed information could not find a relay node in its vicinity with a shorter Euclidean distance to the destination the node is then known as a void node and the upward area in this node's sphere is known as a void area. In the depth-based routing protocols, nodes use their depths to forward the sensed information to reach the water surface. The sensed information is forwarded from the packet generator through the intermediate nodes with lesser depth to the water surface. In this class of routing protocols, if a node holding sensed information could not communicate with another node in its vicinity that has a lesser depth than itself, then this node is known as a void node and the area above this node is known as a void area. Thus, a void area or a communication void area among underwater nodes is where the lack of nodes in the area exists as shown in Figure 4-1. A void area is considered as one of the major issues to investigate in the UWSNs field. This void area is able to block the collaboration between two or more nodes in the network and as a consequence causes a topology partition that leads to reduced network connectivity and causes packet loss, which as a result decreases the overall network performance.

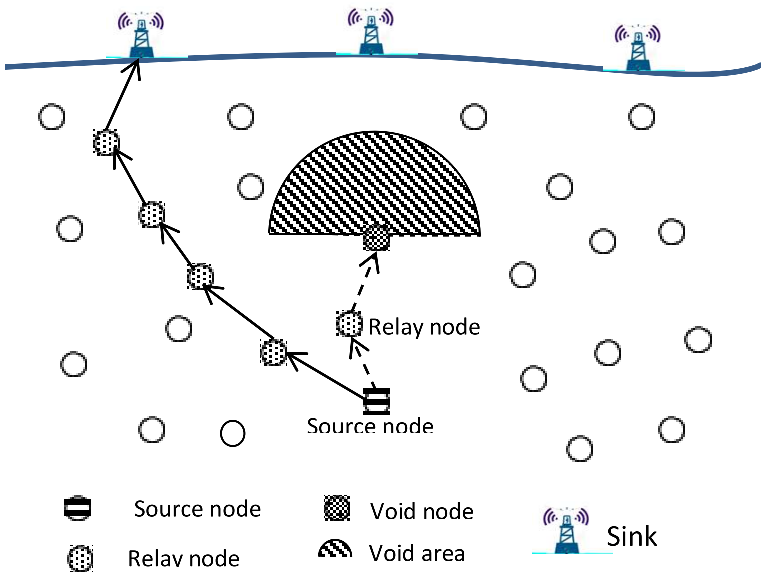


Figure 4-1: Void Area in UWSNs Architecture

Through our studies and literature investigation we conclude that the void area phenomena can occur in any network architecture as a consequence of one or more of the following reasons we listed below:

1- ***Sparse topology deployment***: the high cost of underwater sensor nodes can lead to utilizing an insufficient number of underwater sensor nodes to observe the area of interest. This can create a sparse sensor node topology deployment; consequently, void areas are more likely to be established.

2- ***Underwater sensors failure:*** due to the harsh nature and the characteristics of the underwater environment, the sensors are more likely to fail because of corrosion and fouling and this may cause a void area problem.

3- ***Underwater sensor nodes movement:*** the underwater sensor nodes move in horizontal and vertical directions due to the water current. This node movement will change the node locations and may create a void area.

4- ***Temporary obstacles:*** the underwater environment is full of live creatures. The movement of creatures may block the communication link between underwater sensor nodes. In addition, ships, boats and other machines on the water surface may also block the communication link. As a result, a void area may exist.

5- ***The acoustic channel features:*** the acoustic communication channel is affected by the underwater environment characteristics, where the quality and the strength of the signal changes at various water depths, because of unsettled pressure, temperature and salinity at different water levels. The acoustic channel also suffers from high attenuation, channel fading, noise and channel limited bandwidth. All these limitations will decrease the communication efficiency among the underwater nodes and make the void area issue more challenging.

4.3 Network System and Assumptions

In our UWSN architecture model, the underwater network area is a three-dimensional field. The model consists of multiple immobile sinks located on the water surface and a number of underwater sensor nodes randomly deployed in different depth levels and they are assumed to remain static and do not change their location. The sinks are equipped with both radio and acoustic modems. They use radio modems to communicate with each other and/or with a base station, while acoustic modems are used to communicate with the underwater sensor nodes. The underwater sensor nodes are homogeneous in terms of energy, communication and processing capabilities, they all have the same fixed transmission range R_{tx}. The underwater sensor nodes in our model are divided into two types: nodes that participate in data packet forwarding process which are source node, next forwarder nodes, and forwarding candidates, and nodes that do not participate in packet forwarding process, which are void nodes, trapped nodes, and idle nodes. The description of each type of these nodes is given below:

1. Nodes that participate in packet forwarding process (i.e. nodes that play a part in transmitting data packets)
    - The source node is a node that detected the phenomena of interest. It has the gathered information to transfer to the sink(s) on the water surface.
    - Next forwarder nodes are the source nodes for the next hops; they are chosen as best forwarding nodes from the set of forwarding candidates based on the protocol criteria to continue the forwarding procedure.
    - Forwarding candidates are other candidate nodes in the forwarding set that may become sources for the next hop if the higher priority candidates (next forwarder nodes) fail in forwarding the data packets.
2. Nodes that do not participate in the packet forwarding process (i.e. nodes that are not involved in transmitting the data packets)
    - Void nodes are nodes that have the least depth among their neighbor nodes, and they are not within range of a sink. Therefore, they cannot find any node in their vicinity that has less depth than themselves to assist continuing the forwarding process and deliver the packet to its destination.

- Trapped nodes are nodes in which the only node in transmission range with less depth than themselves is a void node or a node whose only path to nodes of lesser depth leads to a void node. That is, the only nodes of lesser depth that are in range of a trapped node are a void node or other trapped nodes.
- The idle nodes are those nodes that are not in a given source, forwarding candidate set and sink vicinities, which making them outside of a given source to sink transmission process.

The network scenario shown in Figure 4-2 demonstrates our network architecture model and the possible routing paths from a given source node to on surface sinks.

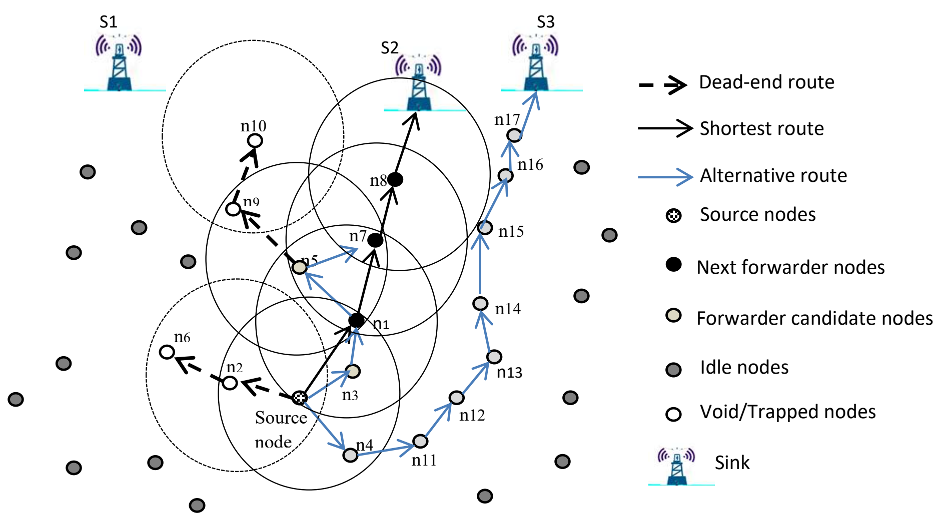


Figure 4-2: Underwater Network Architecture Model

4.4 Proposed EEDOR-VA Routing Protocol for UWSNs

This chapter is intended to design an opportunistic void avoidance routing protocol for UWSNs. Our proposed protocol enhances the overall network performance of the EEDOR protocol by addressing the void area problem, which is why we called it

EEDOR-VA. In order to overcome the void area problem, we utilize bypassing the void and trapped nodes in our system. In greedy protocols, the most appropriate node is selected based on some criteria (e.g. energy, degree, hop count, etc.) to transmit the data packet first. In this manner, other suitable candidate nodes based on other criteria can be suppressed from forwarding the data packets based on other criteria. Consequently, the forwarded data packet might get lost, decreasing the packet delivery ratio, and energy consumption may increase due to retransmission. Our proposal overcomes this weakness by developing a hop-count discovery process. Hop Count Request (HCREQ) and Hop Count Reply (HCREP) messages are used in the process to update the node's reachability information (node's hop count to the reachable closest sink) and to check if the next forwarding candidate node has a path to the sink(s) so it can carry on delivering the packet hop by hop or not. In this way, EEDOR-VA avoids selecting void/trapped nodes and makes the routing decision according to the updated reachability information.

The routing operation of EEDOR-VA protocol is divided into three phases: a hop-count discovery phase, a forwarding set formation phase and a data packet-forwarding phase. These phases will be described in detail in the following subsections.

4.4.1 Methodology

The objective key of our work (EEDOR-VA) is to determine multiple loop-free routes which connect a source node with a single or multiple sinks on the sea surface. This is accomplished through the hop-count discovery technique. Moreover, in EEDOR-VA any void/trapped node in the source and/or relay nodes vicinity do not reply to the HCREQ message, which prevents them from being a part of the forwarding candidates. The established multiple routes make it easy for the protocol to modify the chosen route from one path to another by electing the next relay nodes from a different path if this relay node is the best choice in the next hop forwarding set. Therefore, through this technique relay nodes (i.e. between source node and sink(s)) do not need to initiate hop-count discovery process to learn their hop count. Instead, they can learn their hop count from is hop-count discovery process initiated by the source node. Thus, our proposal uses the route information to update intermediate nodes information and guarantees that nodes responding to the packet holder (P_{holder}) have a path to at least one of the sink(s) to bypass the void nodes.

Figure 4-2 presents a simple example that demonstrates the operations of the EEDOR-VA protocol. From the figure, when the source node has a packet to send, it first sends out HCREQ and all its neighbors, *n1, n2, n3* and *n4* receive it. When a node receives HCREQ for the first time it records the sender as its previous node. When the node later receives the corresponding HCREP it will unicast the HCREP to its previous node. Each of these neighbors rebroadcasts the request to its neighbors. When sinks *s2* and *s3* receive the request message, each sink generates a HCREP and unicasts it downwards. Consider the reply from *s2*. Node *s2*'s neighbor *n8* updates its hop count and unicasts the HCREP to n7. Then node n7 will update the HCREP with its depth and hop count then unicast the reply. This will continue hop by hop until the source node gets the reply.

4.4.2 Hop-Count Discovery Phase

The benefit earned by implementing the proposed hop-count discovery mechanism is to assist any source node as well as the intermediate nodes in the network to determine its hop count to sinks in the network, whether directly reachable within the transmission range or reachable via one or more hops through intermediate nodes.

a) **Hop-Count Request Procedure:** First, a source node generates the Hop Count Request message (HCREQ) comprising of a sequence number and the source's ID and broadcasts it to its neighbors. Each neighbor node receives the HCREQ, updates its neighboring table with source ID and maintains the request sequence number. If the request with this sequence number is received for the first time, then the neighbor node records the source node as its previous node, replaces the source's ID with its ID in the HCREQ and rebroadcasts it to its neighbors. Otherwise, the node just ignores the HCREQ. This procedure is repeated until the HCREQ reaches the destination (one of the sinks).

The pseudo code for this procedure is presented in Algorithm 1.

Algorithm 1: Hop-count request procedure:

```
node (n_i) has a packet to transmit
n_i generates HCREQ message  //Node n_i HCREQ (ID n_i, sequence#)
n_i broadcasts HCREQ
node n_j receives the HCREQ
IF n_j is not a sink
    n_j updates its neighboring table
    IF n_j received the HCREQ for the first time
        nj's previous node is ni
        n_j replaces its ID in the HCREQ  //Node n_j HCREQ ( ID n_j, sequence#)
        n_j rebroadcasts the HCREQ
    ELSE
        n_j Ignores the HCREQ
    ENDIF
ELSE
    call Hop-count reply procedure
ENDIF
```

b) **Hop-Count Reply Procedure:** At the beginning, the hop count of on-surface sinks is initialized as 0. Once a sink receives a HCREQ message, it starts a hop-count reply procedure. The sink generates a HCREP consisting of sink's ID, sink's previous node ID, sink's depth, sink's hop count and the sequence number, and sends the reply. When the sink's previous node receives the HCREP with the same sequence number, the node then extracts the HCREP sender's hop count from the reply message and compares it with its hop count to update its information. That is, if the node's hop count is greater than the extracted hop count + 1, then the HCREP receiver node will update its hop count and assign itself a new hop count by increasing the hop count in the received HCREP by 1. Otherwise, if the hop count of the HCREP receiver is less than or equal to the hop count extracted from the HCREP, then the node will ignore the HCREP and keeps its already assigned hop count.

   Once the HCREP receiver updates its information, if this receiver node is not the HCREQ generator (source node) then this node will update the HCREP within its own information (i.e. node ID, previous node ID, depth, hop count and sequence number) and unicasts it to its previous node. Otherwise, if the HCREP receiver is the source node, it will not rebroadcast the HCREP and get ready for the next phase.

The steps of this procedure are summarized in the following Algorithm 2.

Algorithm 2: Hop-count reply procedure:

```
sinks hop count ← 0
sink receives HCREQ
sink initiates HCREP //HCREP format (sink's ID, sink's previous ID,
                                sink's depth, sink's hop count, sequence#)
sink unicasts the HCREP to its previous node
node ni receives an HCREP
IF ni is the destination of the HCREP
    ni extract the hop count from HCREP
    IF ni's hop count > extracted hop count+1
        ni's hop count ← the extracted hop count + 1
        IF ni is not the source node THEN
            ni updates the HCREP (ni's ID, ni's previous node ID, ni's depth,
                ni's hop count, sequence#)
            ni unicasts the HCREP to its previous node
        ELSE
            prepare for the forwarding set selection procedure
        ENDIF
    ELSE
        ni Ignores the HCREP
    ENDIF
ELSE
    ni Ignores the HCREP
ENDIF
```

For simplicity, we present the following example illustrated in Figure 4-3 to clarify the hop-count discovery process of EEDOR-VA. At the beginning of each round of the proposed protocol, the deployed nodes start gathering data of interest from the surrounding environment. As soon as a node (n1) has a data packet to transmit, it starts the hop-count discovery process in attempt to reach at least one of the sinks on the surface (S1). This current source (n1) generates a HCREQ consisting of its ID (n1) and a sequence number and broadcasts it to its one-hop neighbors (n2, n3, n4 and n10). Each of these neighbors (n2, n3, n4 and n10) receives the HCREQ message, replaces its ID in the request and rebroadcasts it to its neighbors to continue the hop-count discovery algorithm until the sinks (S1, S2 and S3) receive the HCREQ message. The paths of HCREQ messages received for the first time are shown as solid line in the subfigure a). The paths of HCREP messages are shown as dotted lines and the hop count of nodes are shown in parentheses in subfigure b).

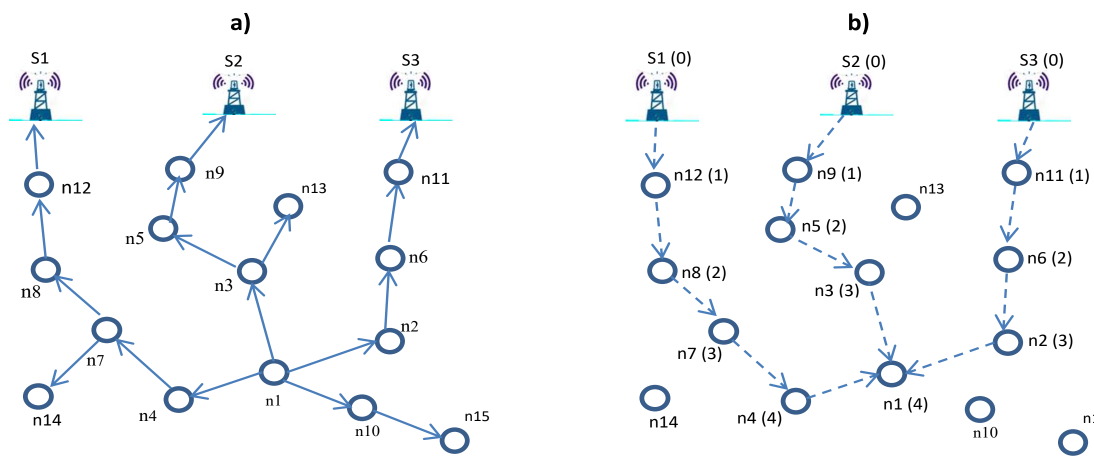


Figure 4-3: Hop-count Discovery Phases: a) HCREQ Path from Source Node n1 to Sinks (s1, s2, s3. b) HCREP Path from Sinks (s1, s2, s3) to Source Node n1

When sinks S1, S2 and S3 receive the HCREQ messages they generate an HCREP messages. As S1's previous node is n12, the HCREP from S1 is unicast to n12. Similarly, the HCREP from S2 is unicast to n9 and from S3 is unicast to n11. When n12, n9 and n11 receive the HCREP messages they update their hop count to 1 and unicast the HCREP message to their previous nodes n8, n5 and n6 respectively. This process continues until the source node, n1, receives the HCREP messages. Each node along the paths of the HCREP messages determines its hop count and forwarding set.

4.4.3 Forwarding Set Formation Phase

When a node is the destination of an HCREP message it will update its hop count and add the sender of the message to its forwarding set if appropriate. Algorithm 3 summarizes the forwarding set selection for any P_{holder} node (i.e. source or next-hop forwarding node).

Algorithm 3: Forwarding set selection

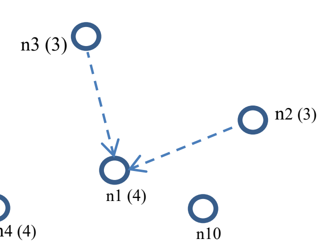
source receives HCREP
IF source receives HCREP directly from a sink // sink in the source transmission range
    The source reduces its forwarding set to the sink and transmit the packet
    Packet delivered to the sink
ELSE // source receives HCREP via relay nodes
  FOR $n_i \in$ source neighbors for which the source is the destination of the HCREP
      IF ni hop count < source hop count
        add n_i to source forwarding set
      ENDIF
  ENDFOR
Sort source Forwarding set // Hop count is considered first then depth in case of a tie
ENDIF

In the EEDOR-VA protocol, if the P_{holder} is not the sink, then we assume one of the two possible cases:

1. If one of the sinks is in a P_{holder} transmission range, then that sink will send HCREP with hop count equals 0 directly to P_{holder} node (i.e. hop count of P_{holder} equals 1). In this case, the P_{holder} reduces its forwarding set to the sink and transmits the data packet.

2. If the current P_{holder} node cannot reach any of the sinks directly (i.e. hop count of P_{holder} greater than 1), then a group of intermediate nodes is nominated to form a next-hop forwarding set.

Each P_{holder} forms its next-hop forwarder set based on the extracted candidate information (IDs, depth and hop count) received with HCREP responses. Once the P_{holder} receives the HCREP from the candidate nodes it checks each candidate's hop count and compares it with its own hop count. P_{holder} then inserts the candidate node into its next-hop forwarding set only if the hop count of this candidate is less than the P_{holder} hop count no matter if it has less or more depth than the P_{holder}. From the example illustrated in Figure 4-3, node n1 received an HCREP message from n2, n3 and n4, which received HCREP messages from nodes n6, n5 and n7 respectively, each having lower hop counts than themselves. Hence, n1's forwarding set illustrated in Figure 4-4 consists of n2 and n3 only while n4 will be eliminated because its hop count is not less than n1's hop count. Note that the forwarding sets of nodes n9 and n11 are sinks. This technique leads to lower energy waste by removing the candidates with higher hop count from the forwarding set. Furthermore, the technique reduces the number of retransmissions as well as energy consumption. The P_{holder} node now knows its forwarding set nodes.



n1 neighbors (n2, n3, n4, n10)

n1 neighbor candidates (n2, n3, n4)

n1 forwarding set candidates (n2, n3)

Figure 4-4: Forwarding Set Formation Phase

After the current P_{holder} node determines its next-hop forwarding candidates set, it sorts the selected candidate nodes in a list based on their hop count from the sink. In the case if two or more nodes having the same hop count from the sink, their depths will be used to break the tie. At each hop, only the list of sorted forwarding candidate IDs will be sent out along with the data packet.

4.4.4 Data Packet Forwarding Phase

After P_{holder} forms its next-hop forwarding set it integrates the data packet with the sorted list of the selected forwarding candidate IDs and transmits it to its neighbors. Each neighbor node receiving the data packets will check if its ID is one of the IDs attached to the data packet or not. A neighbor node simply drops the packet if it could not find its ID in the attached list. Otherwise, the neighbor node has been chosen as a forwarding candidate and it starts the next step by computing its holding time using Equation 4-1below. In the EEDOR-VA protocol, the node's hop count is considered as the first metric to determine the most appropriate forwarding node then node's depth will be used as a second metric in case of a tie. The most appropriate forwarding node will have zero holding time before transmitting the data packet to continue the forwarding procedure. If the most appropriate node successfully forwards the packet, and other forwarding candidates overhear the transmission, they will drop the packet. If not, the next node in the sorted list will transmit the data packet, and so on. These steps will be repeated hop by hop until the data packet reaches the sink or all the candidate nodes in the forwarding set fail.

Holding Time calculation: As we mentioned in subsection 3.3.4, generally, the number of nodes that may have the same depth and/or distance from the sinks or the P_{holder} node becomes larger when node density increases. A number of greedy protocols use the node's depth to calculate the node's holding time others use distance between nodes. Hence, the number of nodes with nearly equal transmission time increases, collisions and re-transmission also increase resulting in excessive network energy consumption. Therefore, the holding time in our protocol, which is used to calculate the forwarding time, must fulfill the two following conditions: 1) A node's holding time should decrease with a decrease in node hop count to the sink and node depth. 2) The holding time must also be sufficiently long to allow the lower priority candidate nodes in the forwarding set to hear the packet transmission by higher priority nodes before they forward the same data packet.

Our proposed protocol satisfies the above-mentioned conditions. First, all the candidates in the forwarding set are sorted by the source/P_{holder} in ascending order based on their hop count to the sink and their depth is used to break any ties. Then based on their indices in the sorted list each candidate will be assigned a rank value. A node's rank value increases with the increase of its hop count. This can sufficiently prolong the holding time of nodes with lower priority to satisfy the second condition.

Equation 4-1 is used to calculate the candidate's node holding time (*HT*) in sec.

$$HT = \frac{\left(2 * \frac{R_{tx}}{s}\right)}{D_{diff}} * \left(R_{tx} - D_{diff}\right) * (Rank - 1) \qquad 4\text{-}1$$

Where R_{tx} is the node's transmission range in m, s is the propagation speed of sound in underwater (1500 m/sec.) and D_{diff} in m is the difference between the packet sender depth and the depth of its next forwarder.

In Equation 4-1, the first term aims to balance the propagation delays from the current P_{holder} node to all candidate nodes in the forwarding set. The second term of the equation is used to guarantee that the closer the candidate node is to the surface the shorter the holding time. Finally, the third term assures a unique holding time for each candidate node based on its Rank value. Rank is the index of the node's ID ordered based on their hop count as a first metric and depth as a second one to break the tie when two or more candidates have the same hop count and depth. Note that Equation 4-1 is similar to Equation 3-1 except that Rank here in Equation 4-1 is based on the node's hop count while in Equation 3-1 the Rank is based on the node's depth.

As in EEDOR, the most appropriate node will be at the top of the forwarding set list and have a rank (*Rank*) of 1. It will start its transmission immediately because its holding time will be 0, while the other nodes will suppress their transmission for a different period of time while their holding time is not expired. They will drop the packet if they hear the best forwarder node transmission. Using Rank guarantees that all forwarding set nodes, including those with equal hop counts and depths have different holding times so that their transmissions will not collide. Using depth difference, D_{diff}, between nodes gives a larger holding time to nodes closer to the source, making short hops less likely.

4.4.5 Acoustic Channel Model

Sensor nodes in wireless sensor networks are battery-powered devices. Nodes in UWSNs consume significant amount of energy in their communication because of the underwater acoustic channel characteristics. When the sensor nodes deplete their batteries, the sensor networks eventually cannot operate correctly. In the EEDOR-VA proposal, we improve the routing performance of EEDOR presented in [17], therefore, the same Thorp propagation model, ambient noise, the bit error rate (*BER*) and the probability of a packet delivery (*P*) described in subsection 2.2.4 are used to model the underwater acoustic channel for EEDOR-VA.

4.5 Simulation Experiments

To evaluate and analyze the performance of the EEDOR-VA protocol for UWSNs we compare it with the original EEDOR and DBR protocols through simulation experiments conducted in MATLAB. By bypassing the void and trapped nodes in our novel forwarding set formation, we enhance the reliability of the network through increasing the packet delivery ratio. Furthermore, through our novel EEDOR-VA proposal the network connectivity is retained as the node energy decreases by means of minimizing both the packet duplication and retransmissions, which decreases the packet collisions. In our research, two different scenarios are simulated using the network topologies that exist in [17, 18] and [20, 85]. Since void areas are more likely to exist in networks having small number of nodes, we chose to evaluate the EEDOR-VA with this type of network. In fact, since EEDOR-VA works well with these network topologies, it is pertinent to state that it is also works well when increasing the number of nodes due to the low probability of void area existence.

To assess the efficiency of the proposed EEDOR-VA protocol, we evaluate it with other protocols considering the metrics that elaborated below:

1. **Total Energy Consumption (E_{total}),** denotes the total energy consumed in the two phases a) hop-count discovery phase; including transmitting and receiving HCREQ and HCREP messages, and b) data packets forwarding phase; including transmitting, receiving, and idling energy consumption. The total energy consumption is a cumulative summation that starts at 0. This can be calculated mathematically as:

$$E_{total} = \sum_{i=1}^{rounds} \sum_{j=1}^{n} (E_{init} - E_{resd}) \quad 4\text{-}2$$

   where *rounds* are the number of simulation rounds, n is the number of underwater sensor nodes, E_{init} in J, is the sensor node initial energy, and E_{resd} in J, is the sensor node residual energy. Note that the energy consumed at each node due to computation is not considered it in our calculations.

2. **Mean Energy consumption per node (E_{Mean}),** which is defined as the average of the total energy consumption. Mathematically, E_{Mean} is computed as:

$$E_{Mean} = E_{total}/n \quad 4\text{-}3$$

   where E_{total} in J, is the total energy consumption calculated by Equation 4-2 and n is the number of deployed nodes.

3. **Total number of transmissions (N_{trans}),** denotes the total number of nodes that forward the data packet starting from the source node to reach one of the sinks on the surface. N_{trans} can be presented mathematically as follow:

$$N_{trans} = \sum_{i=0}^{rounds} FN \qquad 4\text{-}4$$

where *rounds* are the number of simulation rounds, *FN* is the number of transmitting nodes in one round.

4. **Packet Delivery Ratio (*PDR*),** which is defined as the ratio of the total number of distinctive packets received successfully at any of the sinks ($P_{success}$) to the total number of generated packets (P_{sent}). We calculate *PDR* mathematically as:

$$PDR = P_{success} / P_{sent} \qquad 4\text{-}5$$

4.5.1 Scenario #1: Simulation Parameters

In the first scenario, we implemented the three protocols utilizing the simulation parameters were initialized in [17, 18]. The power consumed by nodes in transmitting, receiving and idling is 2 watts, 0.1 watts and 0.01milliwatts respectively; the communication parameters are similar to those on a commercial acoustic modem, LinkQuest UWM1000 [87]. For DBR, we used a depth threshold of zero, as used in compered study [18]. Other simulation parameters are summarized in Table 4-1 below. In this scenario, the void avoidance protocol EEDOR-VA is compared with EEDOR proposed in our previous work [17] where EEDOR was shown to be superior to various other algorithms. We also consider the well-known DBR [18] in our comparison results because it is the first depth-based protocol. Statistical and comparison results between the three protocols presented in this section were obtained using 100 runs of our simulation.

Table 4-1: Summary of Scenario one Simulation Parameters

Parameters	Value
Network size	500m×500m×500m
Number of sinks	5
Number of nodes	200 – 800
Maximum transmission range	100m
Distribution	Random
Initial energy	70 J
Data packet size	50 bytes
Data rate	10^4 bps
Frequency	25 kHz

4.5.2 `Scenario #1: Results and Analysis

A. Total Energy Consumption:

This metric was calculated for the three protocols through implementing Equation 4-2 and the results illustrated in Figure 4-5. The greedy flooding technique to forward the data packets from the source nodes to reach the surface sink(s) used by DBR results in a several numbers of transmissions occurring at the same time, which makes collisions between the transmitted packets more likely to happen. Moreover, the depth threshold mechanism used by DBR for selecting next-hop forwarding nodes affects the overall energy consumption by reducing the number of relay nodes. Reducing the number of relay nodes increases the probability of packet loss and therefore increases retransmissions, which increases the energy consumption, and this makes DBR have the largest total energy consumption as we can observe from Figure 4-5. In contrast, the total energy consumed by EEDOR is almost constant and the reason behind that is the network density has an insignificant effect on the next-hop forwarding method utilized by EEDOR routing protocol. On the other hand, the EEDOR-VA total energy consumption also increases with increasing density of the network. The difference between the total energy consumption in the three protocols, especially between DBR and the other two, EEDOR and EEDOR-VA, increases rapidly with the increase in the density of the network. The large variation of energy consumption shown in Figure 4-5 among the three protocols as the network density increases is caused mainly by an increase in the size of the forwarding sets and redundant transmissions in each hop in DBR as the network become more dense. EEDOR and EEDOR-VA constrain the number of redundant transmissions due to the coordination method executed based on the proposed holding time. However, the hop-count discovery procedure in EEDOR-VA costs the protocol extra energy expenditure.

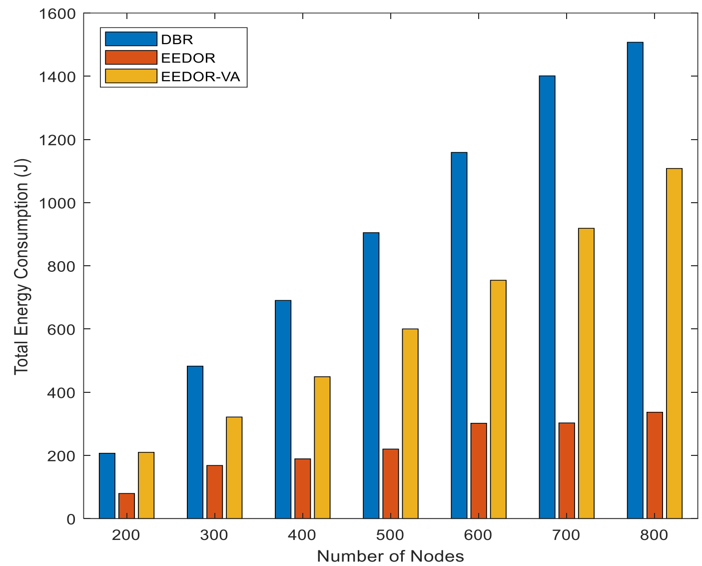


Figure 4-5: Total Energy Consumption vs. Number of Nodes

Additionally, the 95% confidence interval error bars in Figure 4-6 also show that our EEDOR-VA protocol has smaller error range in mean energy consumption per node than the other two protocols. The EEDOR-VA error range decreases as the topology density increases. The small error range indicates that the energy consumption is distributed uniformly around the average and that means more balanced between all nodes. The DBR large variation in mean energy consumption per node as shown by the error bars in Figure 4-6 happens because some of the nodes, especially near the surface, are chosen as a forwarder to retransmit more often than in the others because DBR does not incorporate any energy balancing strategies. The proposed EEDOR and EEDOR-VA waiting time technique in the forwarding set selection phase helps in choosing the next-hop forwarder and balancing the energy consumption by suppressing the retransmissions.

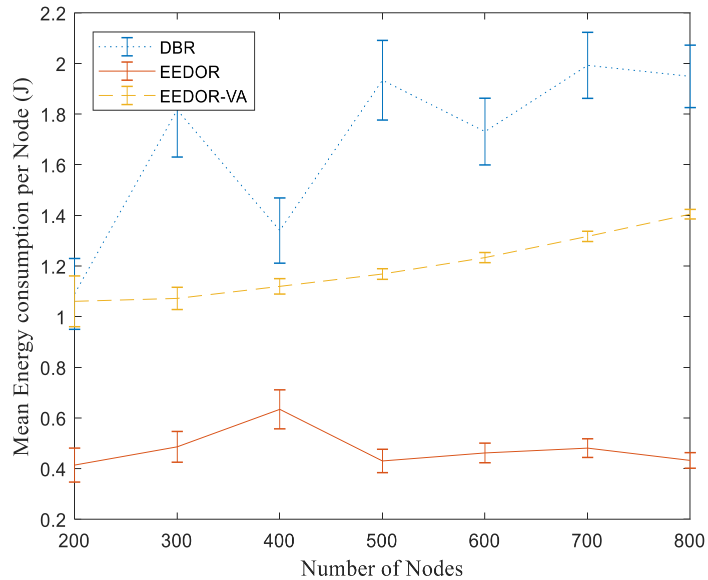


Figure 4-6: Mean Energy Consumption per Node vs. Number of Nodes

B. Packet Delivery Ratio (PDR):

In this network topology, a high value of packet delivery ratio is achieved, as determined by Equation 4-5, meaning that the network is unlikely to have void areas. The PDR demonstrates high values because increasing the number of distributed nodes increases the number of selected forwarding nodes in the routing path and as a result increases the PDR. We can observe from figure 4-7 that, the packet delivery ratio of EEDOR-VA is always higher than that of the two other routing protocols and this is mainly because it omits all the routes that lead to a void area. Our technique can deal with the void problem without implementing any recovery mode as required in [74, 78, 80], which eliminates the recovery mode high overhead and costs.

Furthermore, the packet delivery ratio of DBR and EEDOR is not as high as EEDOR-VA because both the DBR and EEDOR protocols do not take into account if there is at least one route existing between the source and the sink(s) or not. If no route exists, packet forwarding failure is increased since at some point in data transmission, the current packet holder node cannot find any appropriate node with less depth than itself to transmit the data packet to it causing packet loss, which effects the PDR.

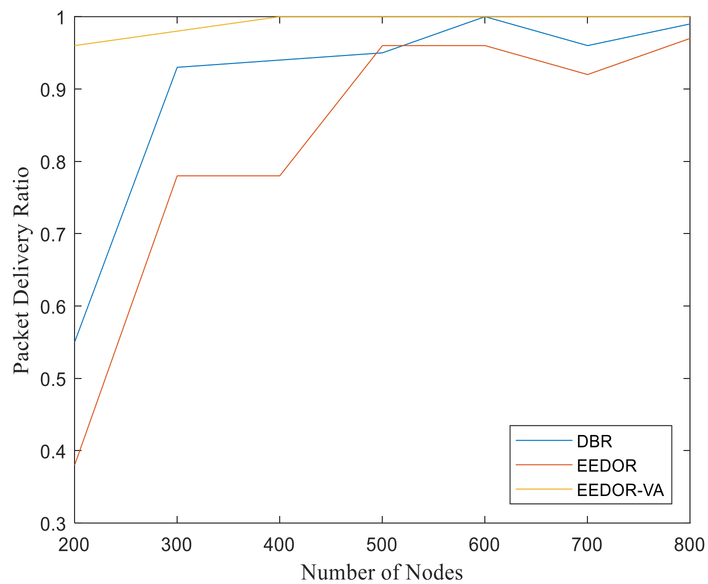


Figure 4-7: Packet Delivery Ratio (PDR) vs. Number of Nodes

We also observe from Figure 4-7 that DBR has a better PDR than EEDOR. DBR's higher PDR results from its use of a greedy mechanism to flood the network with data packets. The flooding mechanism can lead to multiple routing paths that causes redundant packets transmission and facilitate delivery of the packet to the sink(s), which increases the PDR. Conversely, in EEDOR, the current node selects its forwarding set based on the neighboring node depths without identifying void/trapped nodes. If the next forwarder is a void/trapped node (and therefore cannot find any node with less depth than itself), that node drops the received packet, which decreases the EEDOR packet delivery ratio. Finally, we also noticed that the higher PDR achieved by

EEDOR-VA comes at an extra expense of energy cost compared with EEDOR. However, it still achieves higher PDR while using less energy consumption than DBR as illustrated in Figure 4-5.

4.5.3 Scenario #2: Simulation Parameters

This scenario presents the simulation of the second network topology. The list of the configuration parameters used in our experiments is presented in Table 4-2. These simulation parameters were initialized as in [20, 85].

Table 4-2: Summary of Scenario Two Simulation Parameters

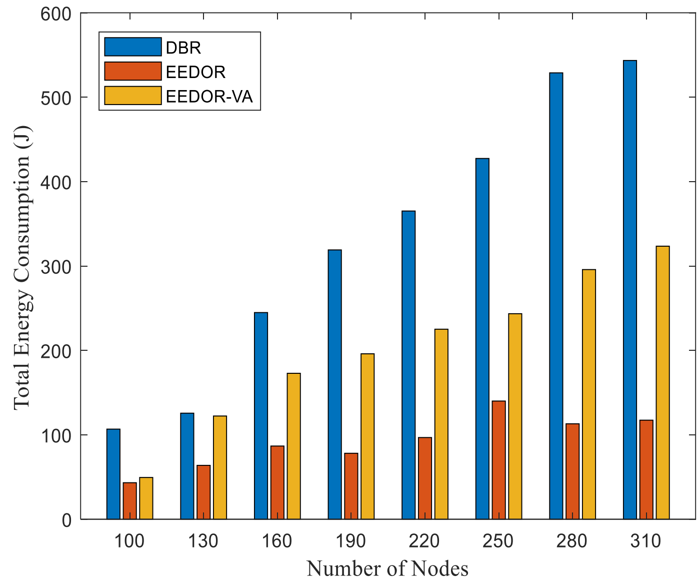
Parameters	Value
Network size	3000m×1500m×3000m
Number of sinks	16
Number of nodes	100 – 310
Distribution	Random
Initial Energy	70 J
Transmission powers	(8.5, 35, 55)W
Maximum transmission range	(500, 1200, 2000) m
Data packet size	150 bytes
Frequency	37.400 kHz
Data rate	18700 bps
s (shipping)	0.5
w (wind)	4

Moreover, the power consumed by nodes used in our simulation is 0.8 watts and 0.01 milliwatts in receiving and idle modes respectively. The depth threshold of DBR is one fourth of maximum communication ranges. In our simulation, a source node was randomly selected among all the randomly deployed nodes. In each simulation run, the destination of all data packets is one of the 16 sinks randomly deployed on the water surface. Statistical and comparison results between EEDOR, EEDOR-VA and DBR presented in this section were obtained using 30 runs of our simulation.

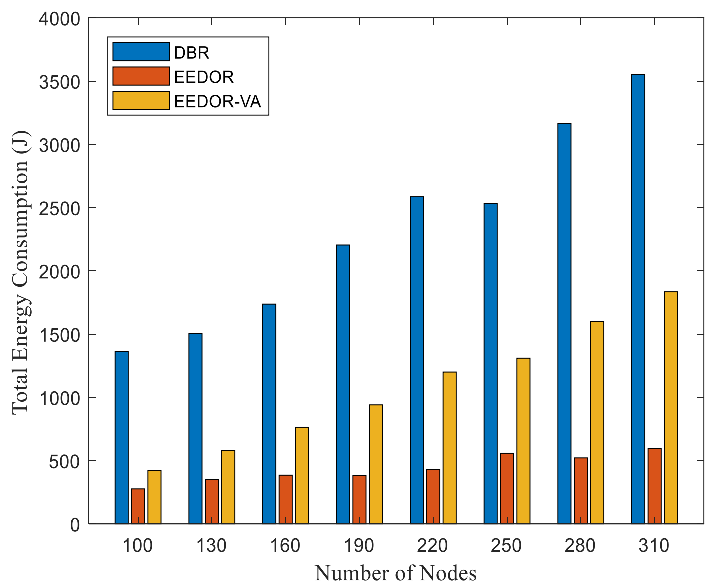
4.5.4 Scenario #2: Results and analysis

A. Total Energy Consumption:

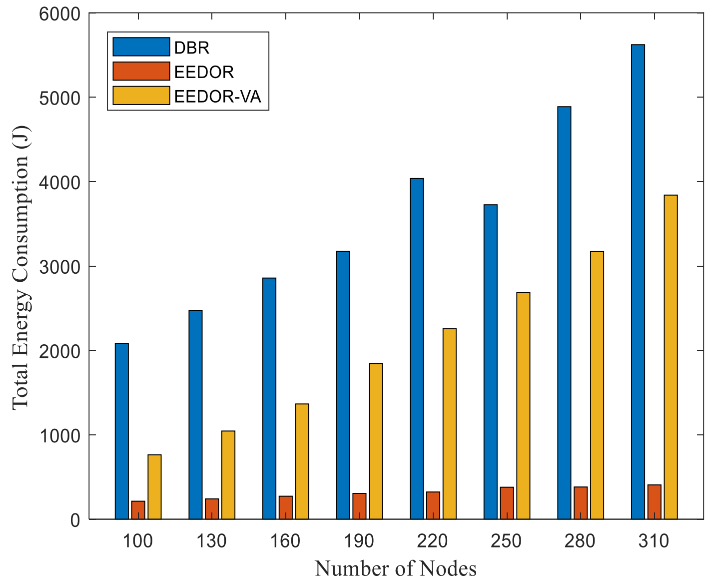
In this scenario, we have three subfigures a), b) and c) in Figure 4-8 that illustrated the total energy consumption of the three protocols at three different power levels that related with the three different communication ranges. As we can see in these subfigures, the transmission power level and node density have direct impact on the total energy consumption. That is, increasing either the power level or the network node density would increase the connections between the deployed nodes in the network topology. A higher connectivity means a larger number of nodes will be participating in the data forwarding procedure thereby increasing the energy consumed. Moreover, we remarked from the figure that, for example, for 100 nodes the total energy consumption increased by approximately 10 times when we increased the power level from 8.5 watts to 35 watts and about 17 times when increased from 8.5 watts to 55 watts. While, for example, in the topology with a transmission level of 8.5 watts, increasing the density of network from 100 nodes to 310 nodes increases the total energy consumption by only about 7 times. Consequently, we can conclude that the power level has more effect on the EEDOR-VA performance in term of total energy consumption than the network density.



(a) Transmission Power=8.5 watt



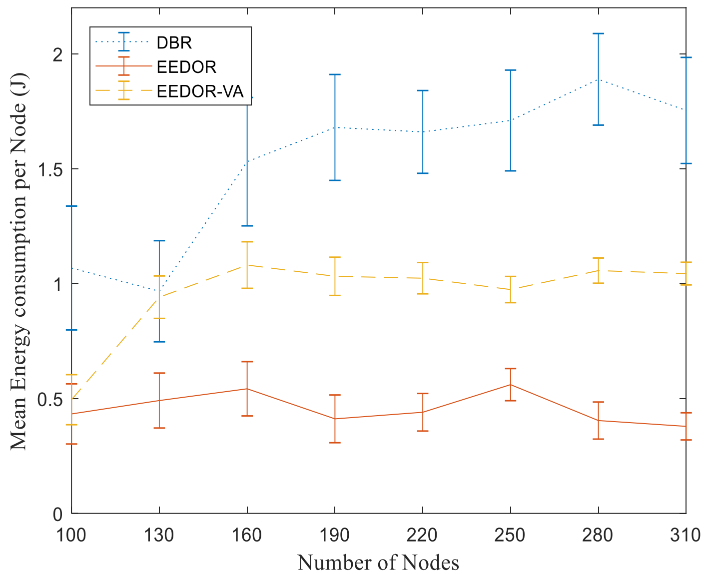
(**b**) Transmission Power=35 watt



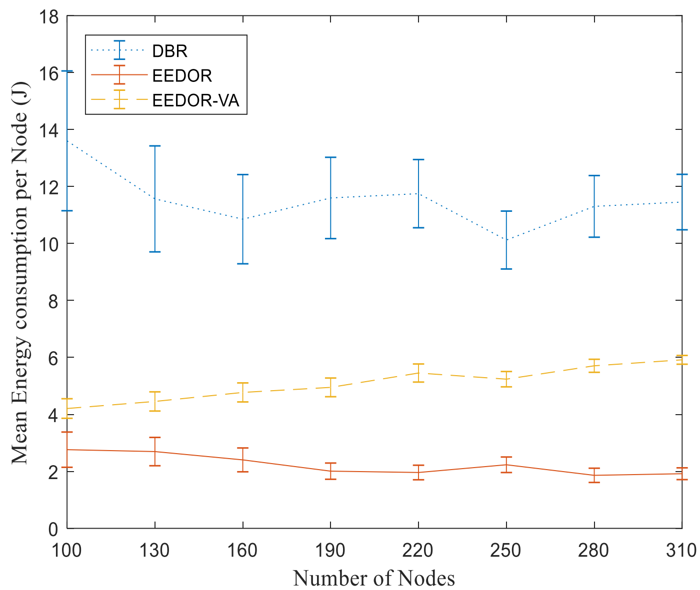
(c) Transmission Power=55 watt

Figure 4-8: Total Energy Consumption at Different Transmission Powers Levels

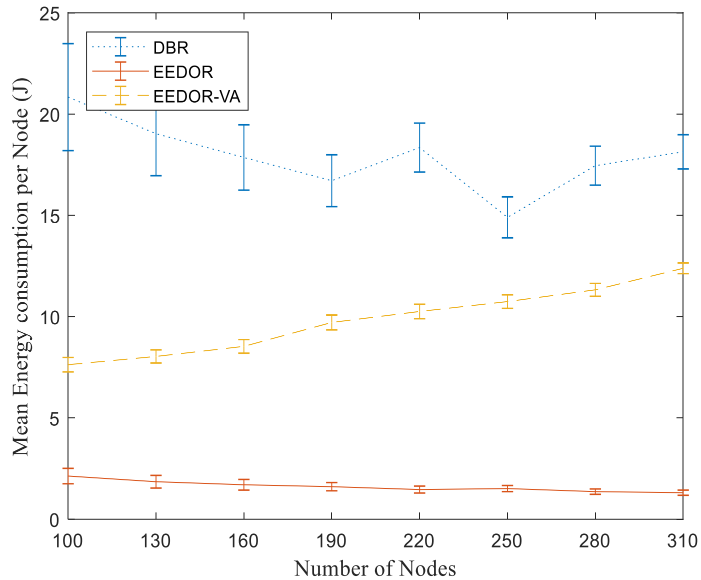
Additionally, the 95% confidence interval error bars in Figure 4-9 show that our EEDOR-VA protocol has smaller error range mainly with low transmission power level. The EEDOR-VA error range decreases as the network density increases. The small error range indicates that the energy depletion is more stable between all the nodes in the topology. In DBR, the large variation in mean energy consumption per node occurs because of the flooding technique where some of the nodes with lesser depth, especially those near the surface, forward more frequently since DBR does not incorporate any energy balancing strategies. The EEDOR and EEDOR-VA waiting time techniques assist in the next-hop forwarder's collaboration to transmit the data packet and balance the energy consumption by suppressing the redundant transmissions.



(a) Transmission Power=8.5 watt



(b) Transmission Power=35 watt



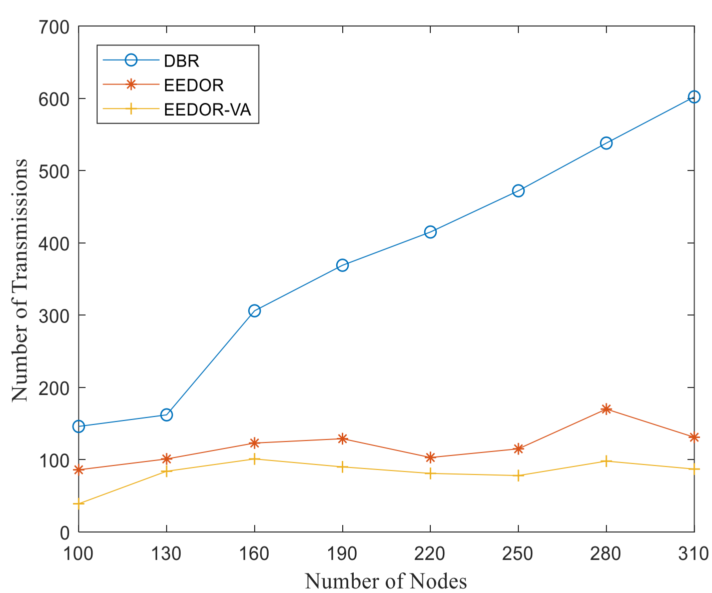
(c) Transmission Power=55 watt

Figure 4-9: Comparison of Mean Total Energy Consumption per Node at Different Transmission Power Levels

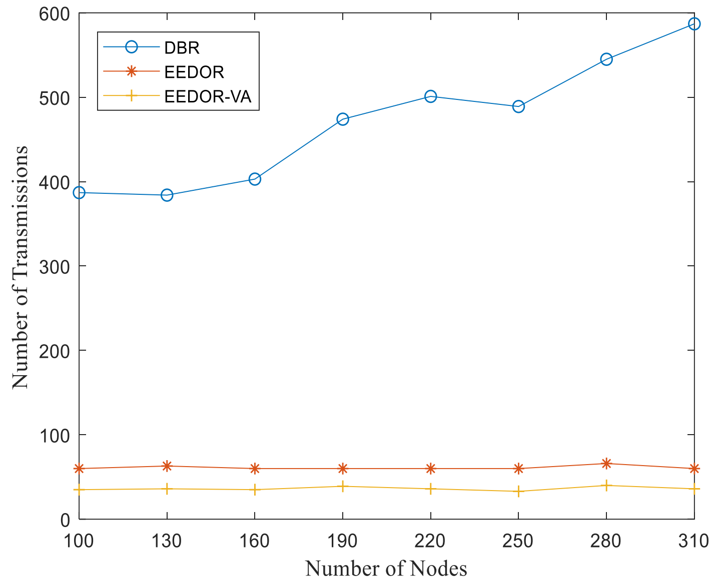
B. Total Number of Transmissions:

Since the energy consumed in transmitting is larger than that consumed in receiving, we implemented Equation 4-4 to determine the total number of nodes participating in data packet transmissions starting from source node until reaching the sink for all three protocols using the three power levels. The objective behind executing this metric is to validate the energy consumption metric and give explanation regarding the extensive variance between the total consumed energy of DBR and both of our protocols EEDOR and EEDOR-VA. Figure 4-10, consists of three subfigures a), b) and c), demonstrates that, DBR has the largest total number of nodes that participated in transmitting the data packets. The number of forwarding nodes in DBR increases rapidly with increasing the network density. This number is almost twice of the number of distributed nodes especially when number of deployed nodes exceeds 130 nodes as appeared in the subfigure a). This growth in the total number of transmitting nodes in the DBR protocol as the network density increases occurs because the protocol utilizes the greedy flooding technique to transmit the data packet.

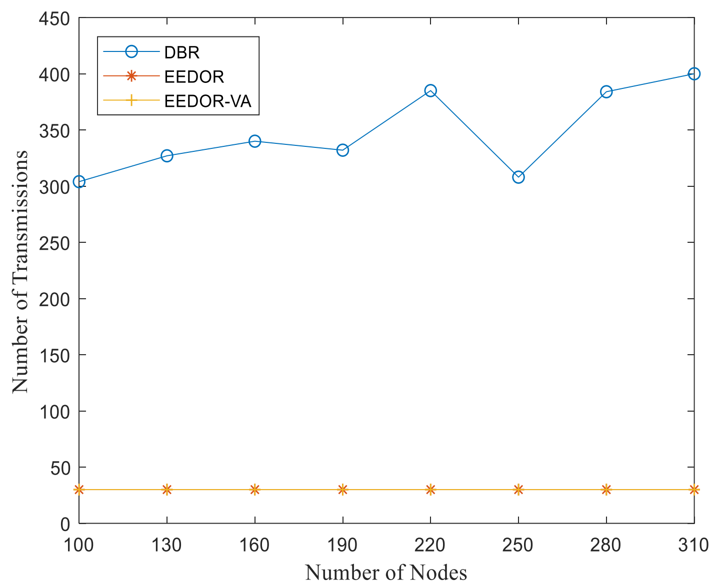
In contrast, the proposed waiting time applied in both EEDOR, and EEDOR-VA helps the forwarding nodes with lower priority to suppress their transmission when they hear the higher priority node transmission. This yields a much smaller total number of transmitting nodes. Moreover, in EEDOR and EEDOR-VA with a higher transmission power level the number of transmitting nodes become closer to each other as shown in the subfigures b) and even equal as shown in subfigure c). Finally, we conclude from Figure 4-10 that, for EEDOR and EEDOR-VA the total number of transmitting nodes is relatively constant with the network density especially with high transmission power levels, while it increases greatly with network density for DBR.



(a) Transmission Power=8.5 watt



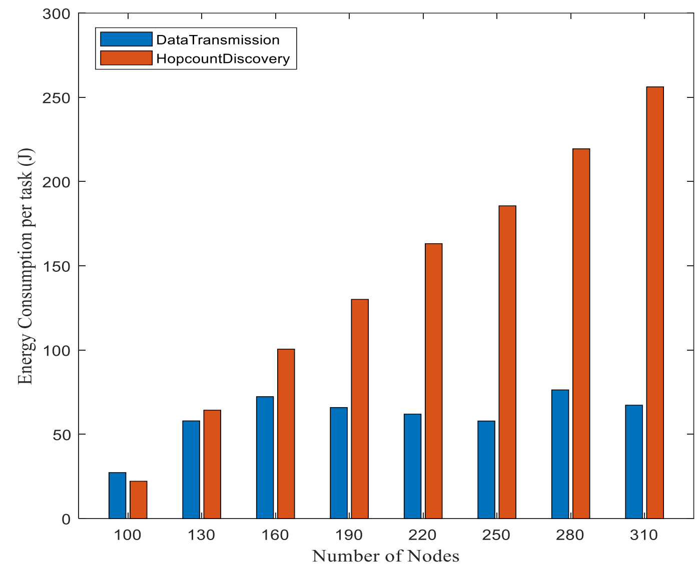
(**b**) Transmission Power=35 watt



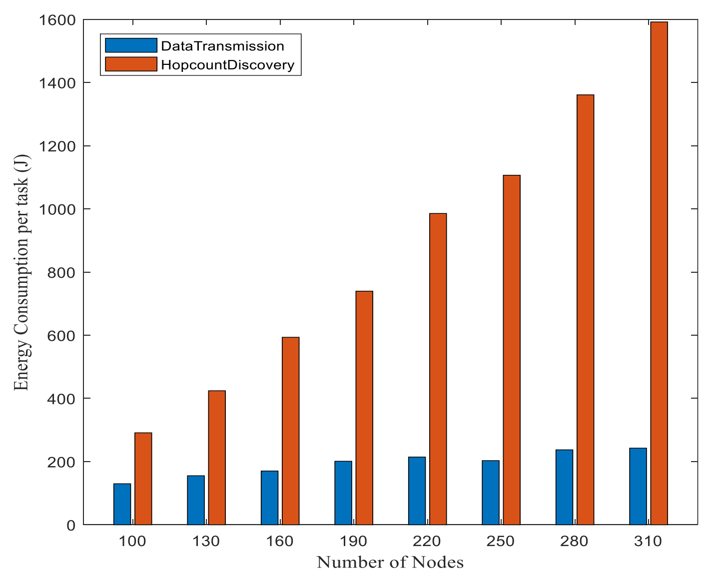
(**c**) Transmission Power=55 watt

Figure 4-10: Number of Transmissions Comparison at Different Transmission Power Levels

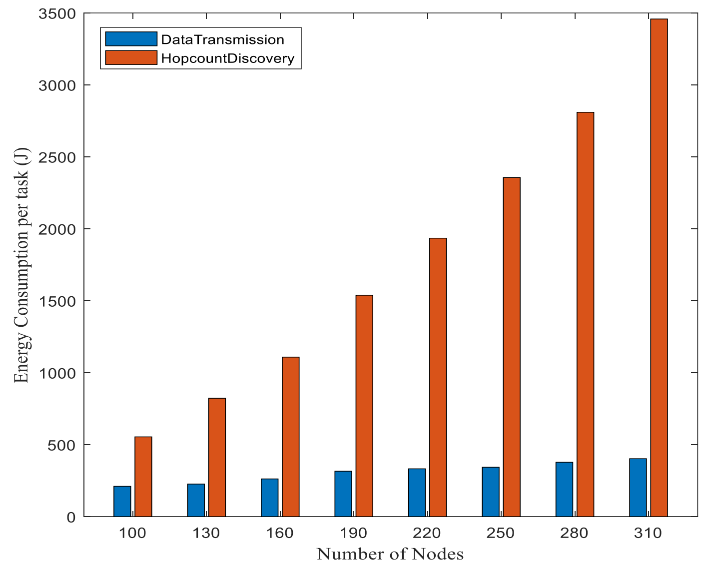
By referring to the subfigures a) and b) in Figure 4-10, we realized that the number of nodes that actually transmit the data packets using EEDOR-VA is less than the number of transmitting nodes when using EEDOR. Motivated by these results we investigate the energy consumed by EEDOR-VA during both hop-count discovery and data transmission phases to detect the extra energy cost. Figure 4-11 illustrates the total energy consumption for hop-count discovery and data transmission processes. As shown in Figure 4-11 the subfigure a), the hop-count discovery phase consumed a slightly less energy than that consumed in data transmission phase when the network topology with 100 nodes is used. This energy consumption similarity in the two phases happens due to suppressing the HCREQ from being broadcasted through the whole network because void areas appearance or links failures and because their size is much smaller than the data packets. Relative energy consumption is reversed when the density of the nodes increases, which increases the number of the nodes that can communicate with each other due to decreasing the void areas. This increase in node connectivity means more nodes will rebroadcast HCREQs to cover all connected nodes, while the data packets will be transmitted hop-by-hop through only the relay nodes with discovered hop count to deliver them to the destination. The same explanation is also true when using a higher transmitting power levels as shown in Figure 4-11 the subfigures b) and c). Thus, the EEDOR-VA hop-count discovery process is responsible for most of the total energy consumption of the network since it broadcasts more widely in the networks than the data packets.



(a) Transmission Power=8.5 watt



(**b**) Transmission Power=35 watt



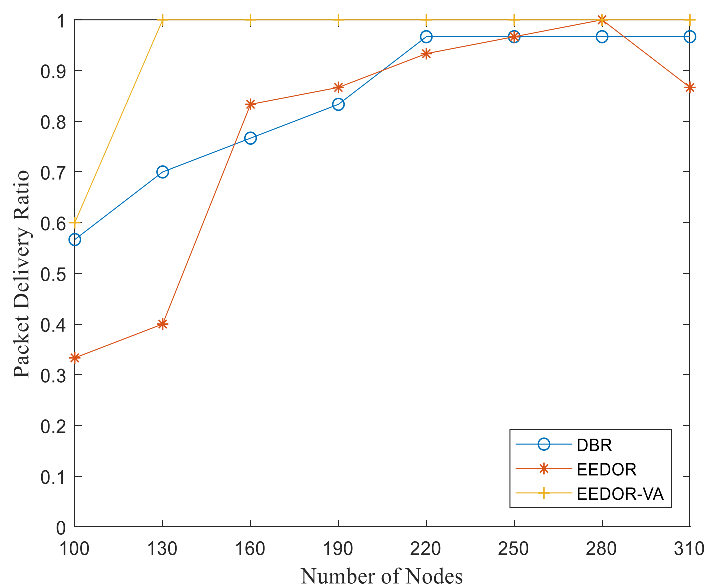
(**c**) Transmission Power=55 watt

Figure 4-11: The Proposal EEDOR-VA Total Energy Consumption per Task at Different Transmission Power Levels

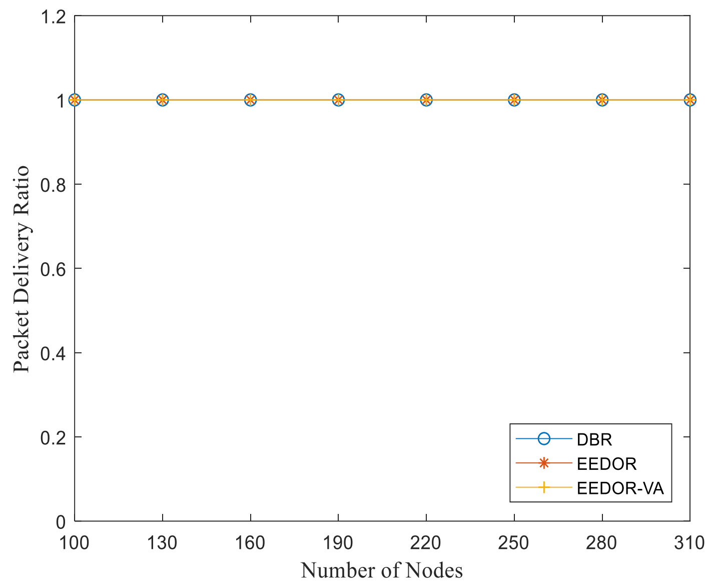
C. Packet Delivery Ratio (PDR):

In this network topology, a lower value of packet delivery ratio of routing protocols is expected since the nodes are deployed far apart from each other, which makes void areas in the network more likely. Moreover, since the sensor nodes may be out of the communication range of each other, the forwarding sets may contain a small number of candidates, or they will be empty and therefore will affect the PDR. We assess the performance of the comparison protocols by decreasing the void nodes in the network through increasing the number of deployed nodes and/or increasing the transmission power level. We simulate the three protocols at three transmitting power levels. Simulation results are shown in Figure 4-12 with its three subfigures a), b) and c). First, the subfigure a) shows that using the smallest power level and the smallest number of nodes in our experiment, EEDOR-VA outperforms

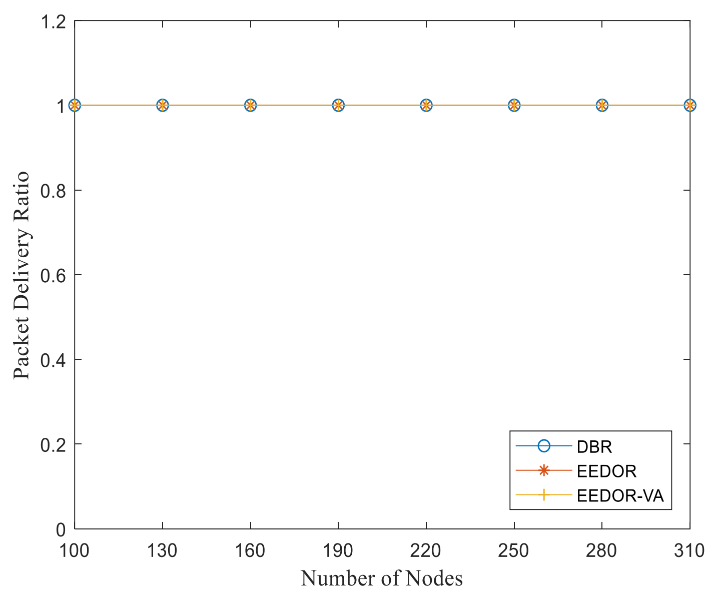
DBR and EEDOR. Increasing the number of nodes at the same power level for EEDOR-VA in Figure 4-12 a) or raising the power level with different number of nodes for the three comparison protocols will help to increase the PDR to the maximum as shown in Figure 4-12 subfigures b) and c). This occurs because an increase in the number of nodes or an increase the power level leads to an increase in the number of next-hop forwarding candidates and this helps to increase the probability of delivering the packet successfully.



(a) Transmission Power=8.5 watt



(**b**) Transmission Power=35 watt



(**c**) Transmission Power=55 watt

Figure 4-12: The Proposed EEDOR-VA Packet Delivery Ratio (PDR) at Different Transmission Power Levels

It is important to mention that, referring to [85], the power control method used by PCR protocol helps to increase the connectivity between the nodes. This increases the number of forwarding candidates. In DBR, the depth threshold mechanism and the large number of disconnected nodes tends to decrease the number of forwarding candidates. This decrease in forwarding candidates explains why, in [85], DBR outperformed the PCR protocol in energy consumption. It also explains the low PDR for DBR compared with the high PDR obtained by the PCR protocol. On the other hand, when we compare DBR with EEDOR-VA, the redundant packets and retransmissions in DBR are the reason for the extra amount of depleted energy. In addition, the collisions in the DBR protocol are caused mainly by redundant packets, which increase the probability of packets being lost and decrease the PDR. For EEDOR-VA, the forwarding candidate priority and holding time reduces the total energy consumption through minimizing the redundant transmissions and the hop-count discovery process maximizes the PDR by guaranteeing that the packet is delivered successfully. It is important to note that the simulation results in both scenarios presented above shows that our proposed EEDOR-VA outperforms DBR and PCR in terms energy usage and PDR.

4.6 Conclusions

In this chapter, we proposed a new OR protocol called EEDOR-VA that can handle the void area communication by bypassing the void areas and detecting void and trapped nodes. In our proposal EEDOR-VA, the void avoidance protocol effectively enhances the network performance by increasing the packet delivery ratio relative to the comparative established protocols [17] and [18], especially in networks having a small number of nodes where the void areas are most likely to occur. Furthermore, EEDOR-VA enhances the reliability of the network by successfully detecting any void/trapped nodes in the source to sink routes by using the hop-count discovery process in advance and before data transmission start. EEDOR-VA also minimizes the packet duplication by reducing the number of nodes that transmit data packets using *Rank* to distinguish between node holding times. This approach helps to decrease the energy expenditure in the data transmission process as well as packet collision and its associated cost.

In this chapter, we studied the efficiency of our proposed EEDOR-VA by examining it in two different network topologies in addition to different transmission power levels in one of the simulated topologies. The analyses of experimental simulation results show that EEDOR-VA enhances network performance in terms of energy consumption, packet delivery ratio and the number of nodes that actually complete the transmitting process.

Chapter 5 **Impact of Surface Sinks on Underwater Routing Performance**

5.1 Overview

In single-sink network topologies, nodes near the sink are used to carry the traffic most often, affecting network performance (i.e., early node death, congestion, etc.). Conversely, multi-sink architectures can enhance UWSNs performance by distributing the traffic loads between more sensor nodes in a way that can balance the energy consumption between deployed nodes. Moreover, an appropriate sink deployment strategy can guarantee a high probability of connectivity between the sinks and underwater sensors and provide a stable network topology for the fulfillment of subsequent monitoring tasks. That is, distributing the tasks fairly between the network nodes that are within transmission range of sink(s) can effectively minimize the overall cost of the network. Also, to ensure that a maximum number of deployed nodes in the network are able to connect with at least one of the sinks, which play a significant role in improving the routing performance, two sink architectures and two deployment strategies were investigated. In this chapter, we use the previous two routing protocols that were proposed in Chapter 3 and Chapter 4 to study the influence of the single-sink and multi-sink architectures on the performance of routing protocols for UWSNs from the packet delivery and energy usage perspective. Our main objective in this chapter is to focus on surface sink(s) in UWSNs. We investigate how the number of sinks, and the deployment strategy can influence network routing in order to offer some insight on designing and implementing UWSNs that are more efficient. Our main contributions are:

1. For the first time, an investigation of the impact of random vs. deterministic sink deployments on the routing protocols performance.

2. The use of deterministically deployed multi-sink topologies in UWSNs. This approach results in more energy conservation and better packet delivery ratio than other sink deployment strategies.

The rest of this chapter is organized as follow: Section 5.2 summarizes sinks topologies and deployments for UWSNs. Simulation results are shown in Section 5.3. Finally, Section 5.4 presents the chapter conclusion.

5.2 Major Sink Topologies in UWSNs

Monitoring wide areas in the water (i.e. sea, ocean) requires designing large-scale UWSNs with large numbers of components (i.e. underwater sensor nodes, sinks, etc.) to ensure the connection between these network components and improve the deployments techniques. Moreover, gathering data from underwater regions of interest where the gathered data is transferred by underwater sensor nodes and collected by surface sink(s) depends on the routing protocols used. It is known that sensor nodes have limited resources, effecting the communication between them as well as with surface sinks. Hence, the greater the area to be monitored the greater the number of sensor nodes and sinks that must be deployed to cover the entire area and assure the maximum connectivity between these nodes and sinks. Based on the number of sinks used in the UWSNs and the routing protocols implemented, each data packet can be transmitted to one or more surface sinks. Depending on the number of sinks used, the UWSN topologies can be classified into: - 1) Single-sink UWSNs where only one sink node is used. 2) Multi-sinks UWSNs, where the network uses two or more sink nodes. Therefore, from the perspective of routing protocols, the number of sink nodes is a crucial factor that has an influence on designing routing protocols and increasing the number of delivered data packets when multiple paths and destinations are made available. Moreover, creating a network with multiple surface sinks arranged intelligently in a way that can mostly or fully cover the water surface improves the performance of the routing protocols. Multiple sink deployment reduces packet duplication and retransmission, increasing the packet delivery and shortening the transmission path where each sensor node transfers the data packets to its closest sink.

5.2.1. UWSNs Topologies Based on Number of Sink(s)

Different numbers of sinks were used in the state-of-the-art OR protocols as summarized in Table 2-1. In this subsection, we present a brief description of the connection between the underwater sensor nodes and the sink nodes by considering the number of deployed sinks. We used ring layers for the single-sink UWSNs and horizontal layers (i.e. tiers) for multi-sinks UWSNs to clarify the hop-by-hop routing path from nodes in deep levels of the water to the sink(s) through relay nodes with less depth.

A. Single-Sink UWSNs Topology

The single-sink UWSNs topology comprises only one sink node to gather the information of interest from underwater sensor nodes via one or multiple hops depending on how far the underwater sensor node is from the surface sink. This single-sink is usually fixed on the water surface in the middle of the monitored area. Figure 5-1 below depicts a simple UWSN topology with a single-sink, ring layer construction and the routing path from a source node to the surface sink.

In Figure 5-1, to keep things simple, the average transmission distance in each forwarding hop is assumed to be as the transmission range of the sensor node (*R)*. In this UWSNs topology, there is only one surface sink node; the ring-layered arrangement around the sink node is exploited to analyze the data forwarding and routing behavior, and underwater nodes deployed at different layers in the shape of ring surrounding the sink node.

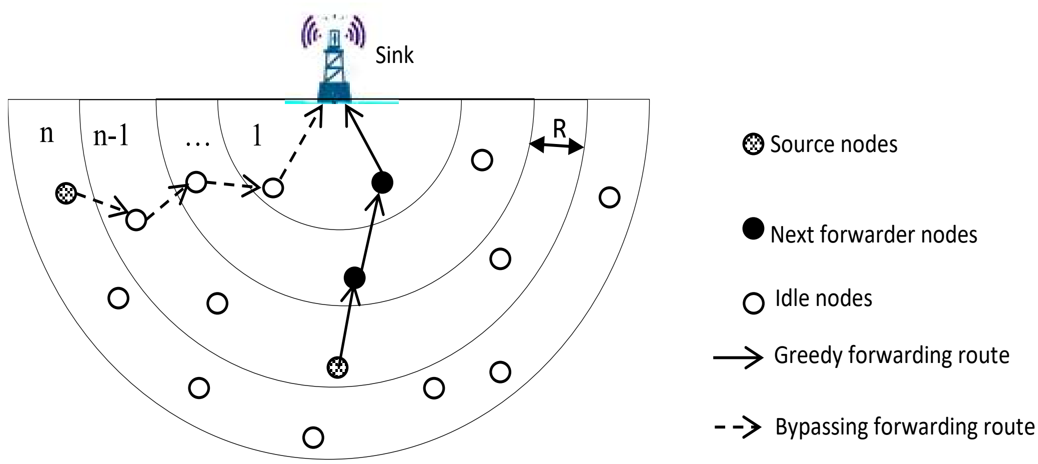


Figure 5-1: Single-sink UWSNs with Ring Layered Construction

It is clear that the greater the distance between the underwater node and the surface sink, the more hops the packet must travel to reach that single sink on the surface. Therefore, the network model is split up into n ring layers based on the distance to the sink node, with each layer having a width of R. From the perspective of the greedy routing, nodes in the first layer, which is the layer near the sink, can transmit their data packets directly within one-hop to the sink, while the i^{th} layer nodes can only send packets to the (i-1) layer nodes. This means that nodes in layer i use multi-hop to forward their packets to the sink. In other words, each data packet forwarded by any node in layer i can only be delivered to the single-sink on the surface after i number of hops. Moreover, these nodes in the i^{th} layer transmit their own data packets as well as other packets received from nodes in the further layer (i.e. i+1 layer). On the other hand, in the bypassing routing technique, nodes in the i^{th} layer can send the packets to the nodes in layer i-1 or layer i +1, using multi-hop to forward collected packets to the sink. In this technique, since the packet forwarding can be directed upward or downward, the number of hops required by any node in layer i to deliver each data packet to the single-sink on the surface is variable. Some routing protocols designers have adopted this UWSNs single-sink topology, such as [76, 80, 81]. The UWSN topologies that use the single-sink suffer from poor connection to that single-sink especially in sparse deployment networks. Congestion at the area near to the sink is also an issue in the UWSN topologies with single-sink more than UWSN topologies with multi-sinks. Furthermore, the underwater sensor nodes surrounding the sink are generally more prone to node failures since they are exploited to relay data to that single-sink more frequently causing early node death, which cause packet loss even if far nodes are still alive.

B. Multi-Sinks UWSNs Topology

The UWSNs with multi-sinks are made up of two or more sink nodes deployed on the water surface. They are used as a destination to receive gathered data from underwater sensor nodes that collect the information and forward data packets to the nearest sink.

In multi-sink UWSNs, an observed area of depth L can be divided into n horizontal layers (i.e. tiers). Each layer has a width of R, equal to the underwater sensor transmission range, as illustrated in Figure 5-2.

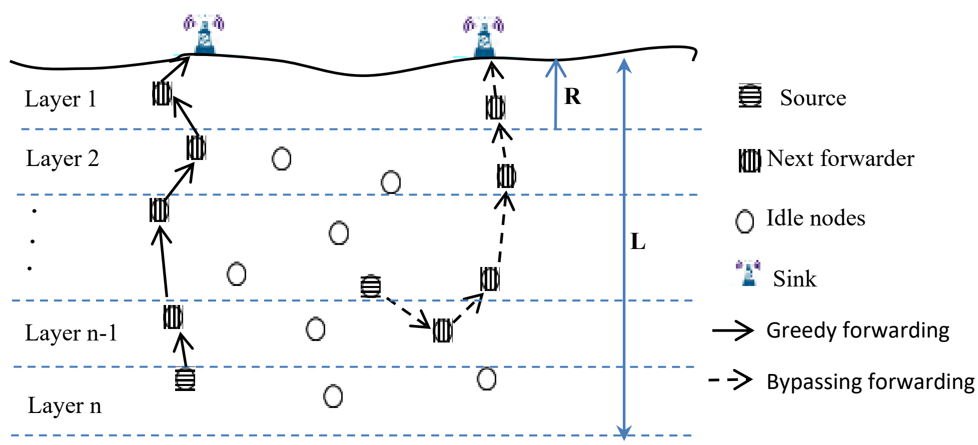


Figure 5-2: Multi-sink UWSNs with Horizontal Layered Construction

In the greedy routing technique, the deeper the node in the water the more hops required for the packet to be delivered to one of the surface sinks. From a routing perspective, nodes in the first layer, closer to the surface water, can send data packets straight to the closest sink in their transmission range with one hop, while the i^{th} layer node can only send packets upward to the connected intermediate node in layer i-1 as shown in Figure 5-2. This means that the layer i nodes can only deliver the packets to the receiver sink through multi-hops. In addition, the less deep nodes in the i^{th} layer forward their own data packets in addition to packets received from nodes in the next deeper layer (i.e. i+1 layer). However, in the bypassing technique underwater nodes can communicate with deeper and shallower depth nodes to establish path(s) to at least one of the sinks. That is, a node in layer i can direct data packets upward to relay nodes in layer i-1 or downward to relay nodes in layer i+1. Exploiting multi-sinks in UWSN topologies is increasingly popular in literature. A number of routing protocols were proposed utilizing multi-sink UWSN topologies, such as [74, 75, 78, 85]. Integrating the multi-sinks UWSNs topologies with OR technique improves the routing protocol's performance, increases packet delivery, shortens the routing path, and distributes the tasks efficiently between the underwater sensor nodes.

5.2.2. Sink Deployment

At the beginning of designing any wireless sensor network, the designer is aware of the number of sensor nodes and sinks to be deployed. Both sinks and node deployment have an effect on the overall performance of the network. The majority of UWSN research has focused on underwater sensor node deployment techniques, while few have focused on surface sink deployment. Since the underwater environment is harsh, random underwater sensor nodes deployment is usually adopted where nodes are distributed by an aircraft, for example, at random locations in an environmental monitoring area. In contrast, sink nodes are deployed on the water surface, making the deployment more flexible and much easier to be reached and detected. Nonetheless, we can classify the sink deployment into 1) Random deployment and 2) Deterministic deployment (i.e. planned deployment).

A. Random Sinks Deployment

Due to UWSN design challenges including underwater harsh underwater environment, communication channel characteristics, underwater device resource restrictions and overall cost, random deployments (sinks and nodes) are considered as the primary option for the majority of commercial and research applications. Random deployments have been widely researched [74, 78, 91]. In the random deployment method, the sink(s) are deployed in a random manner on the water surface of the area of interest. In multi-sink UWSNs topologies, random deployment might result in an uneven scattering of sinks, where the distance between any two sinks is variable and unknown, causing an uncertainty in covering all the surface area without any overlaps and/or gaps. In addition, especially in the harsh environment, random sinks deployment may cause an assortment of issues, for example, undesirable sink or underwater node isolation, non-uniform area coverage, and insufficient connectivity between underwater nodes and sinks. These problems are worse with single-sink UWSNs topologies. However, it is important to state that random deployment is typically the best deployment method if no earlier information about the monitoring area is accessible or if the area of interest is unsafe or intractable [92].

B. Deterministic Sink Deployment

To alleviate the random deployment issues mentioned above, the locations of the sinks need to be chosen carefully and determined before deploying. This deployment technique improves the connection between the network components and assures desirable water surface coverage since the sinks are distributed uniformly and the distance between any two sinks is known. Predetermining sink locations depends on the characteristics of the network (e.g. number of deployed nodes and deployment technique) and the environment (e.g. water features and surface obstacles). Sink deterministic deployment techniques have been reported in literature. For example, [93] one surface sink is deployed initially at the center of the topology surface, [94, 95, 96] employed the mesh deployment technique and [97] distributed the sinks at the corner of the area of interest. Moreover, researchers such as [98] employed sink deterministic deployment by proposing mathematical models to relocate the sinks after they were deployed randomly at the initial phase.

5.3 Simulation Results

The objective of our simulation experiments is to investigate the influence of single-sink and multi-sink deployments, both random and uniform, on routing protocol performance. We conduct experiments using two different evaluation scenarios using the parameter simulation settings used in chapter 3 and chapter4 . In order to validate the effectiveness of surface sink numbers and deployments on the performance of routing protocols, we examine their influence on our two previously proposed routing protocols EEDOR, where the greedy routing is utilized, and EEDOR-VA, where the Hop Count Discovery procedure is implemented.

5.3.1. Impact of Number of Sinks on Routing Protocol Performance

In this section, we study the impact of the number of surface sinks (i.e., single-sink vs. multi-sinks), and we present the results of the routing protocol performance including energy consumption and packet delivery ratio. The sink(s) was (were) randomly deployed, and different random underwater network topologies were used in each simulation run. The same simulation parameters listed in Table 4-1 in chapter 4 are considered here in the first and second scenario respectively; with both EEDOR and EEDOR-VA protocols. We used one sink vs. five sinks in the first scenario and one sink vs. 16 sinks in the second one, in this section sink(s) were deployed randomly, to evaluate how these different number of sinks can affect the routing protocol's performance includes energy consumption and PDR.

5.3.1.1. Scenario #1: Simulation Settings:

We evaluated the performance of EEDOR and EEDOR-VA protocols using one sink and five sinks. The simulation parameters used were those listed in Table 4-1, with 100 different randomly distributed network topologies.

5.3.1.2. Scenario #1: Results and Analysis

This subsection shows the evaluation results and analysis to assess the impact of number of sinks on UWSN topologies formed in the first scenario. The simulation results in terms of total energy consumption for both protocols are illustrated in Figure 5-3 for EEDOR and Figure 5-4 for EEDOR-VA, and in terms of PDR are illustrated in Figure 5-5 for EEDOR and Figure 5-6 for EEDOR-VA using both single-sink and multi-sink protocols.

Figure 5-3 shows how the EEDOR routing protocol nodes' energy consumption varies with different numbers of surface sinks. Less energy is consumed in the multi-sink versus single-sink topology. This may seem surprising given that the EEDOR protocol is carried out almost entirely within the non-sink nodes. However, sinks are involved at the last hop when a node is within transmission range of a sink. Then the node reduces its forwarding set to the that sink. The size of the data packet transmitted is smaller than what it would otherwise be reducing energy consumption. Also, neighboring nodes which would otherwise carry out the Forward Request/Forward Reply process do not do so reducing energy consumption even more.

Figure 5-4 shows how the EEDOR-VA routing protocol node energy consumption varies with different numbers of surface sinks. Less energy is consumed in the multi-sink versus single-sink topology. The reduced energy consumption occurs for the same reason as for EEDOR although the reduction is not as large. In EEDOR-VA a large proportion of energy is consumed by the initial HCREQ flood which does not involve the sinks. Hence, the energy saved in the last hop is a smaller proportion of the total energy.

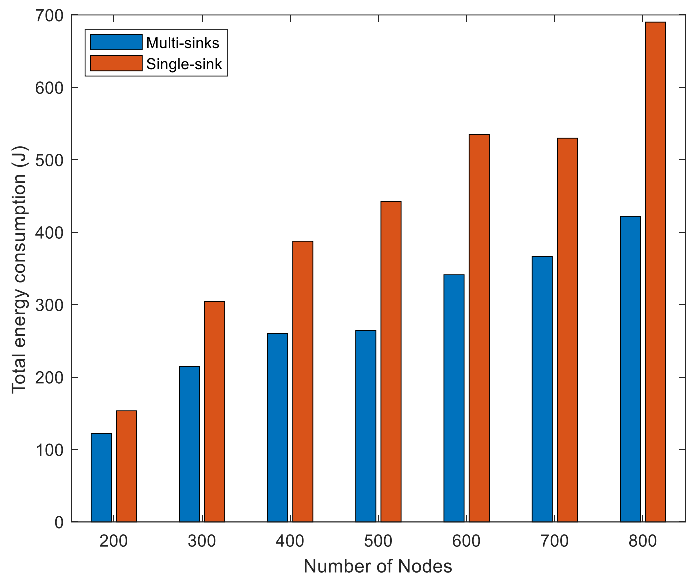


Figure 5-3: Impact of The Number of Sinks on EEDOR Energy Consumption

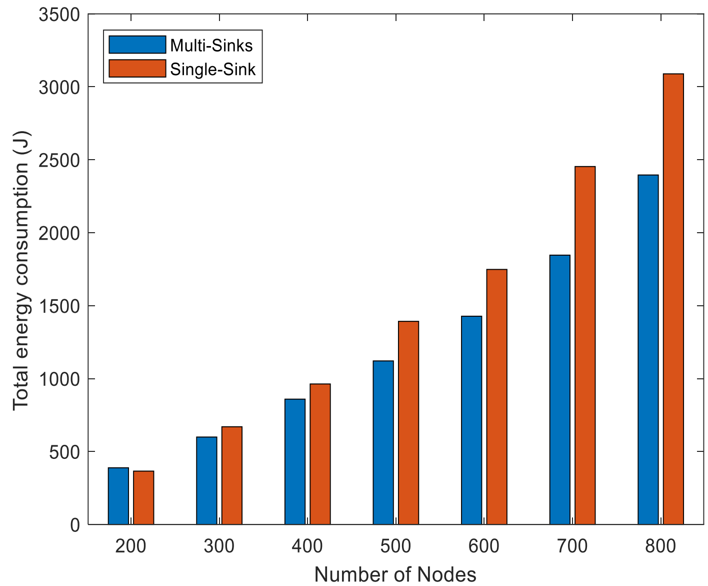


Figure 5-4: Impact of Number of Sinks on EEDOR-VA Total Energy Consumption

Figure 5-5 shows the PDR of the EEDOR routing protocol with multi-sinks vs. single-sink UWSN topologies. A noticeable difference in the PDR can be observed in the network topologies with different number of deployed nodes. Based on the figure, with more sinks on the surface a greater number of sensor nodes will be in transmission range of one of these deployed sinks. That is, the probability of delivering the data packet increases, resulting in a high packet delivery ratio. On the other hand, in the single-sink topologies only small portion of deployed nodes can reach that single sink making the probability of delivering data packets smaller and resulting in decrease the packet delivery ratio.

Figure 5-6 shows the PDR of the EEDOR-VA routing protocol with multi-sinks vs. single-sink UWSN topologies. As for EEDOR the PDR is higher for the multi-sink case. However, once the density of the network increases to 500 nodes there is not a significant difference in PDR.

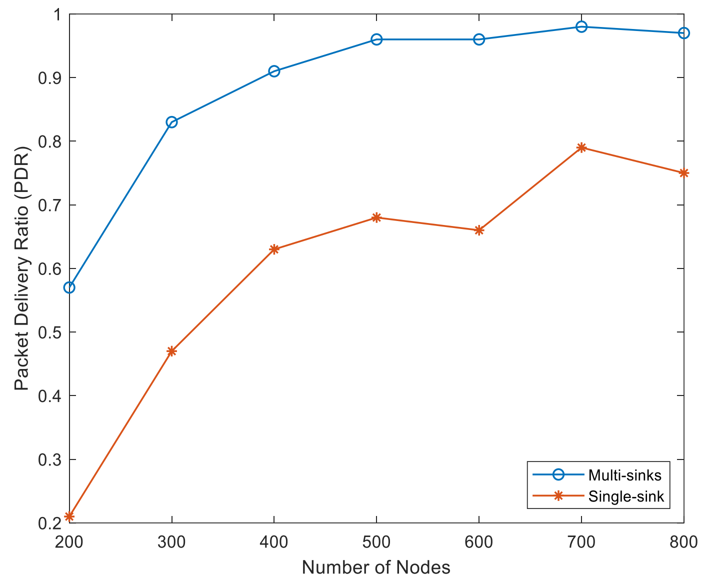


Figure 5-5: Impact of Number of Sinks on EEDOR Packet Delivery Ratio

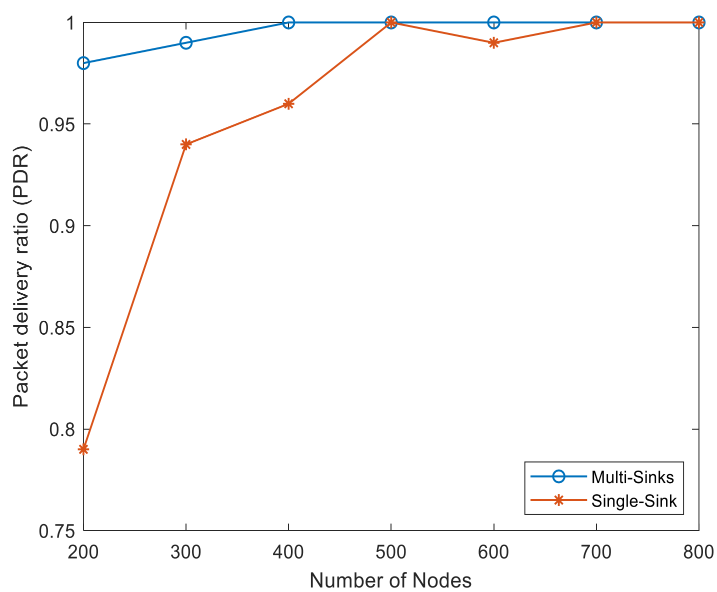


Figure 5-6: Impact of Number of Sinks on EEDOR-VA Packet Delivery Ratio

5.3.1.3. Scenario #2: Simulation Settings:

In the second scenario, we consider the same simulation parameters listed in Table 4-2 with both protocols (i.e. EEDOR and EEDOR-VA). However, for the number of sinks we used one sink vs. 16 sinks deployed in a random manner to evaluate how these different number of sinks UWSN topologies can influence the connection between sink(s) and underwater sensor nodes and affect routing protocols performance.

5.3.1.4. Scenario #2: Results and Analysis

In this subsection, we show the results and analyses of evaluating and assessing the impact of number of sinks (i.e. single-sink vs. multi-sinks) and present the results of the routing performance metrics includes energy consumption and packet delivery ratio. As in the first scenario, the sink(s) are randomly deployed, and different random network topologies are used in each simulation run.

In this scenario, the transmission power level = 8.5 watt is used with one and 16 sinks to evaluate EEDOR and EEDOR-VA protocols in order to assess the routing performance by means of single-sink vs. multi-sinks.

The energy consumption through the routing process in EEDOR and EEDOR-VA is illustrated in Figure 5-7 and Figure 5-8 respectively. For EEDOR protocol, we can see from Figure5-7 that the total energy consumption of single-sink UWSN topologies is greater than the total energy consumption of multi-sinks UWSN topologies for the same reason as stated in scenario #1.

While Figure 5-8 illustrates that, for EEDOR-VA protocol, the total energy consumption of multi-sinks UWSN topologies are also smaller than the total energy consumption of single-sink UWSN topologies for the same reason as stated in scenario #1.

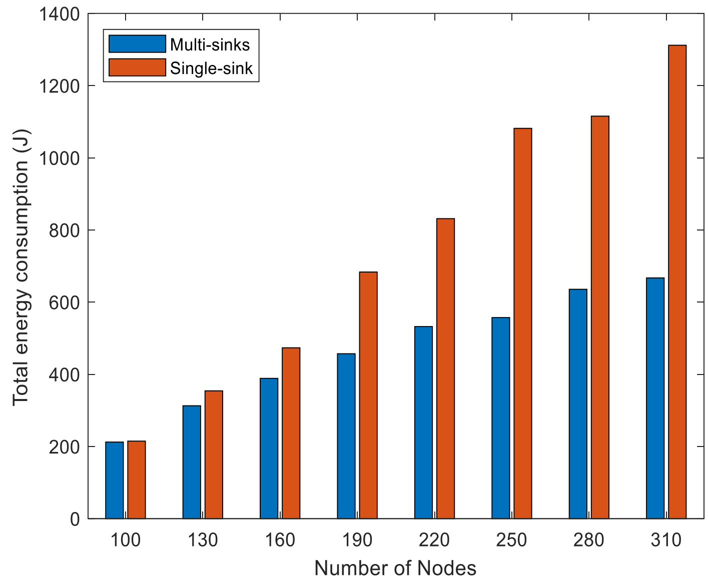


Figure 5-7: Impact of The Number of Sinks on EEDOR Total Energy Consumption

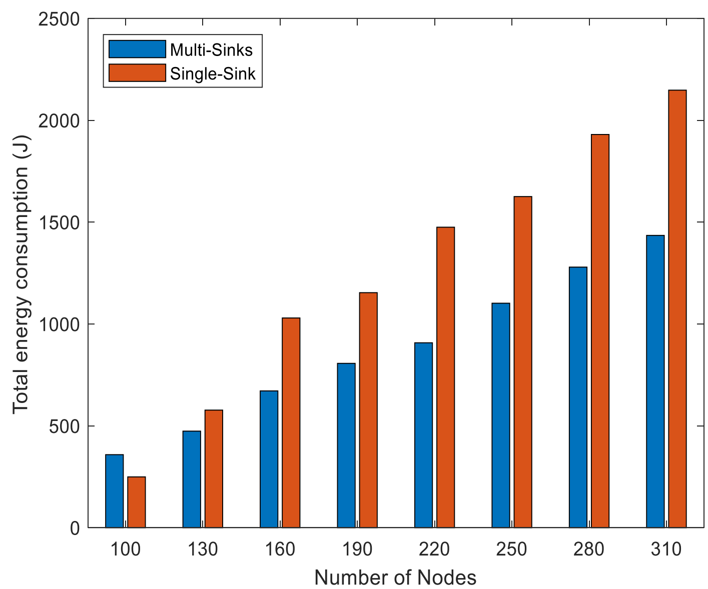


Figure 5-8: Impact of Number of Sinks on EEDOR-VA Total Energy Consumption

In term of PDR, Figure 5-9 presents the PDR for EEDOR routing protocol while Figure 5-10 presents the PDR for EEDOR-VA routing protocol. In Figure 5-9 the PDR for the multi-sink case is higher than that for the single-sink case. The reason is the same as for scenario #1.

In Figure 5-10 we can see that EEDOR-VA with multi-sink topologies achieves a higher PDR than for single-sink topologies. The reason is that same as for scenario #1.

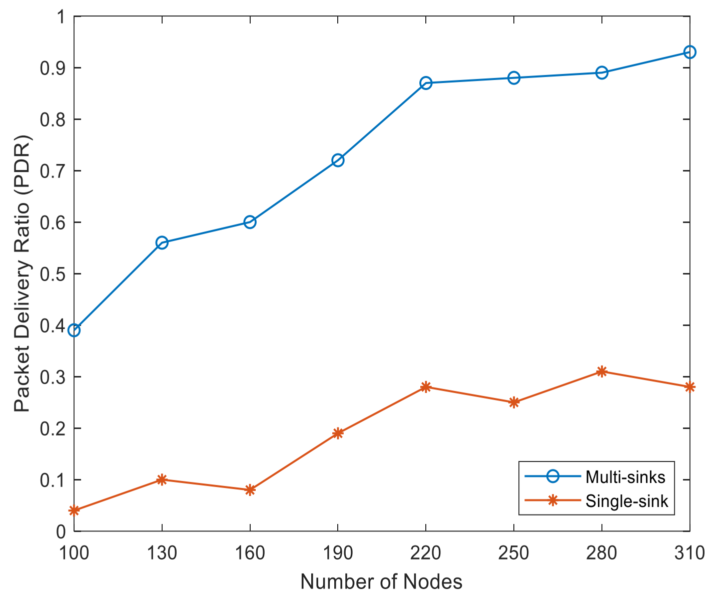


Figure 5-9: Impact of Number of Sinks on PDR of EEDOR Protocol

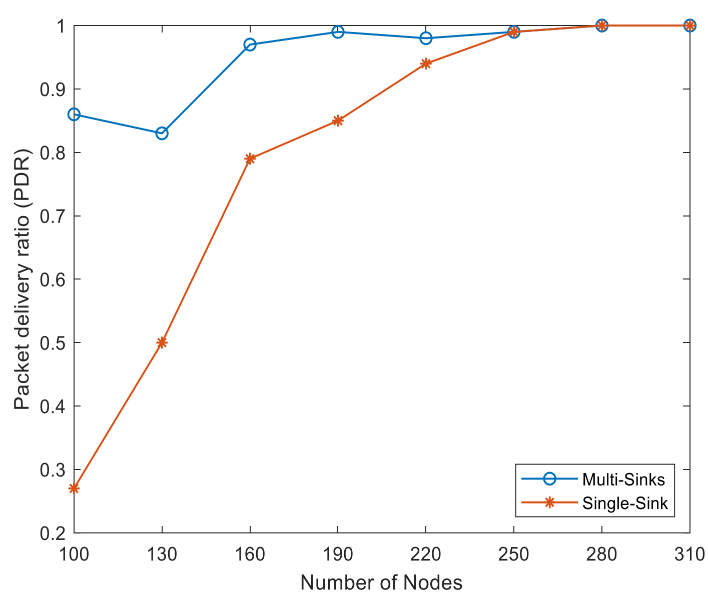


Figure 5-10: Impact of Number of Sinks on EEDOR-VA Packet Delivery Ratio

5.3.2. Impact of Deployment of Surface Sinks on Routing Performance

In this section, multi-sinks UWSN topologies are studied with two different sink deployment strategies, deterministic and random, in order to assess the impact of sinks deployment strategies on the routing protocol performance including energy consumption and packet delivery ratio. As in the previous section, two scenarios are analyzed using the same simulation parameters in Table 4-1 and Table 4-2.

5.3.2.1. Scenario #1: Results and Analysis

Figure 5-11 demonstrates the deterministic deployment of the five sinks we use in our simulation to evaluate EEDOR and EEDOR-VA protocols. In this strategy, we fixed one sink at the middle of the area of interest on the water surface and since the transmission range of deployed nodes is 100m we deployed the other four sinks so that they are 100*m* away from the boundaries of the area of interest in the determined positions (i.e. (100,0,100), (100,0,400), (400,0,100) and (400,0,400)). In contrast, in the random deployment, the sinks' locations are distributed randomly on the water surface without any guarantee the surface area is fully covered by the sinks and the distance between any two sinks is variable.

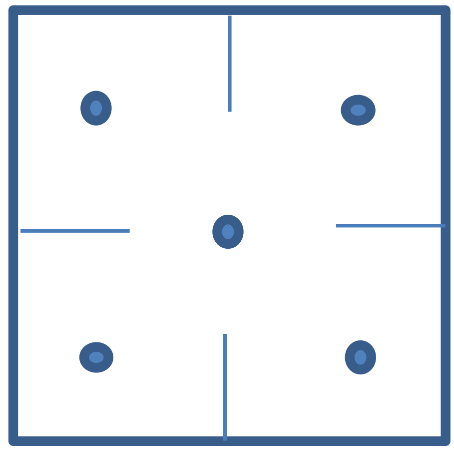


Figure 5-11: Deterministic Deployment of Multi-Sinks (Five Sinks)

In terms of energy consumption, the comparison between the two deployment strategies is demonstrated in Figure 5-12 for the performance of EEDOR and Figure 5-13 related to the performance of EEDOR-VA.

As indicated in Figure 5-12, in the EEDOR, the total energy consumption by the network operations when the surface sinks are randomly deployed is greater than that when deterministic deployment is used to distribute the sinks on the water surface. The deterministic deployment increases the number of nodes that are within transmission range of a sink which decreases the number of forwarding nodes for these nodes. As noted earlier for EEDOR, this reduces energy consumption.

Similar to that, simulation results of EEDOR-VA protocol are illustrated in Figure 5-13. The figure shows that the total energy consumption when the surface sinks are randomly deployed is greater than that when deterministic deployment is used. As for EEDOR, the deterministic deployment increases the number of nodes that are within transmission range of a sink thereby decreasing the total energy consumption.

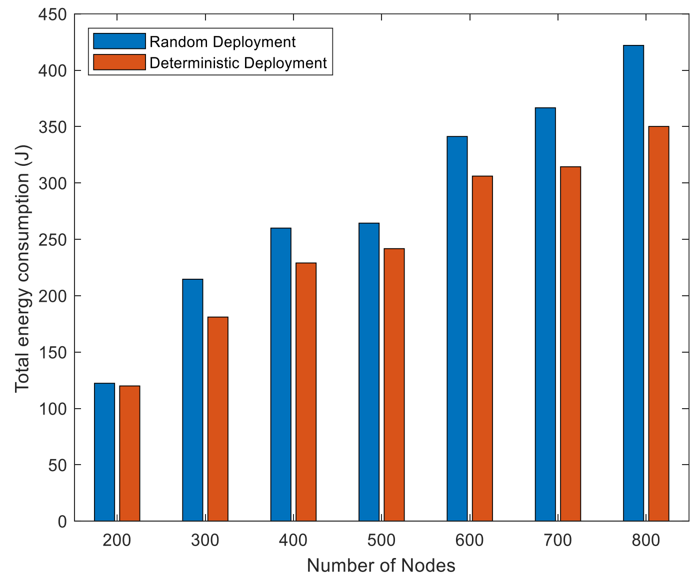


Figure 5-12: Impact of Sinks Deployment Strategy on EEDOR Total Energy Consumption

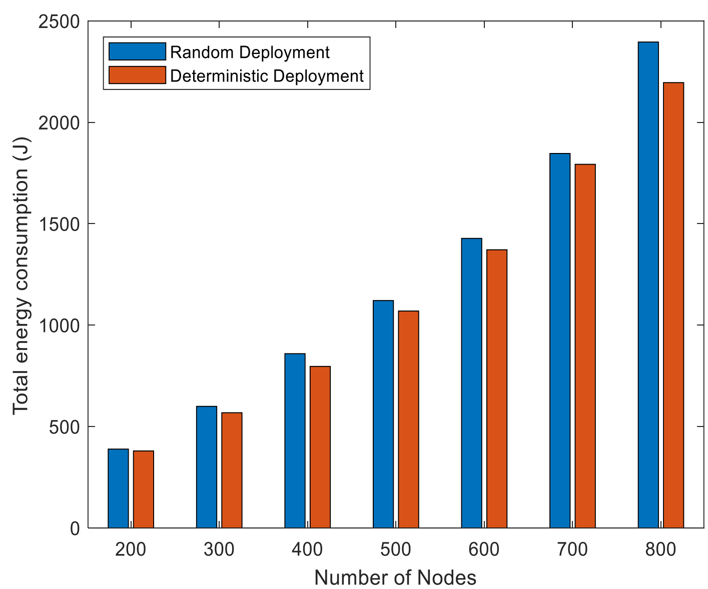


Figure 5-13: Impact of Sinks Deployment on EEDOR-VA Total Energy Consumption

Our simulation results for EEDOR related to the PDR for both sink deployments are illustrated in Figure 5-14. The PDR for deterministic sink deployment is higher than for random sink deployment. The deterministic deployment increases the number of nodes that are within transmission range of one of the sinks which increases the PDR.

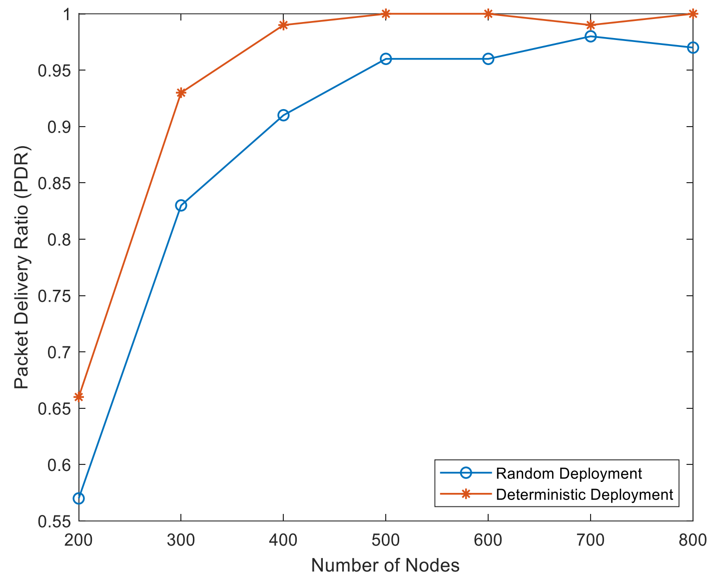


Figure 5-14: Impact of Sinks Deployment Strategy on EEDOR Packet Delivery Ratio

In a contrast, Figure 5-15 shows that the sink deployment strategies have no effect on performance of EEDOR-VA protocol in term of PDR. This is expected as with 5 randomly placed sinks EEDOR-VA has a very high PDR in this scenario.

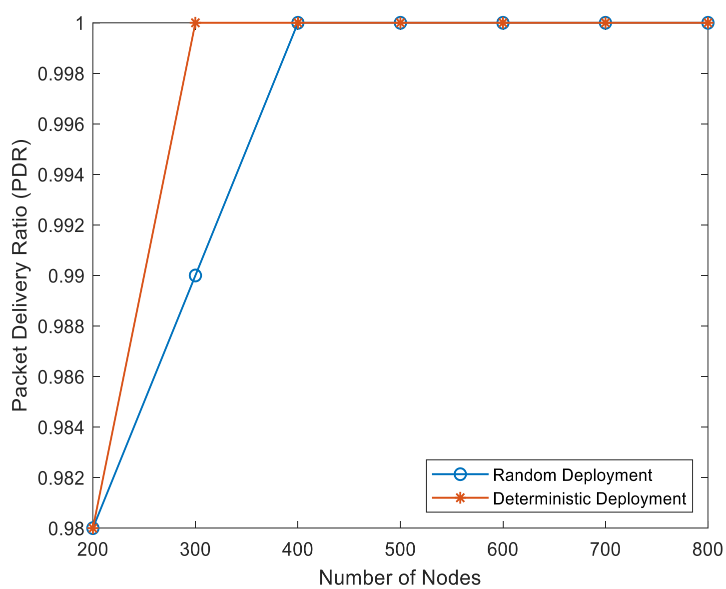


Figure 5-15: Impact of Sinks Deployment Strategy on EEDOR-VA Packet Delivery Ratio

5.3.2.2. **Scenario #2: Results and Analysis**

Figure 5-16 demonstrates the sinks deterministic deployment we use in this scenario to deploy 16 sinks and evaluate the performance of EEDOR and EEDOR-VA protocols. In this deployment strategy, the area of interest on the water surface is divided into grids and the one sink is positioned at the center of each grid cell. While in the random deployment, the sinks are distributed randomly on the water surface without any guarantee the surface area is fully covered by the sinks and the distance between any two sinks is unknown.

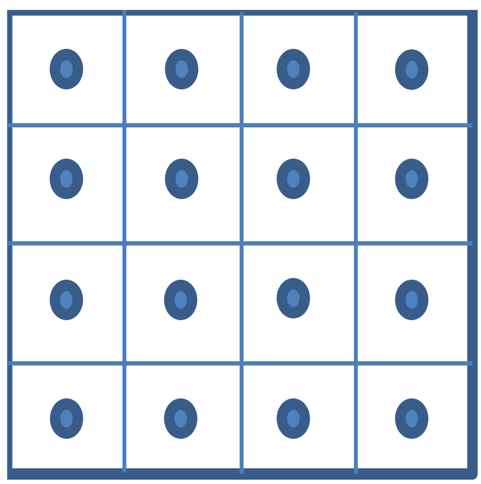


Figure 5-16: Deterministic Deployment of Multi-Sinks (16 Sinks)

In term of energy consumption, the comparison between the two deployment strategies is showed in Figure 5-17 and Figure 5-18.

As indicated in Figure 5-17, in the EEDOR, the total energy consumption by the network operations when the surface sinks are randomly deployed is greater than that when deterministic deployment is used to distribute the sinks on the water surface. The reason is the same as for scenario #1.

In addition, simulation results of EEDOR-VA protocol are illustrated in Figure 5-18. Similar to scenario #1, random deployment uses more energy than deterministic deployment.

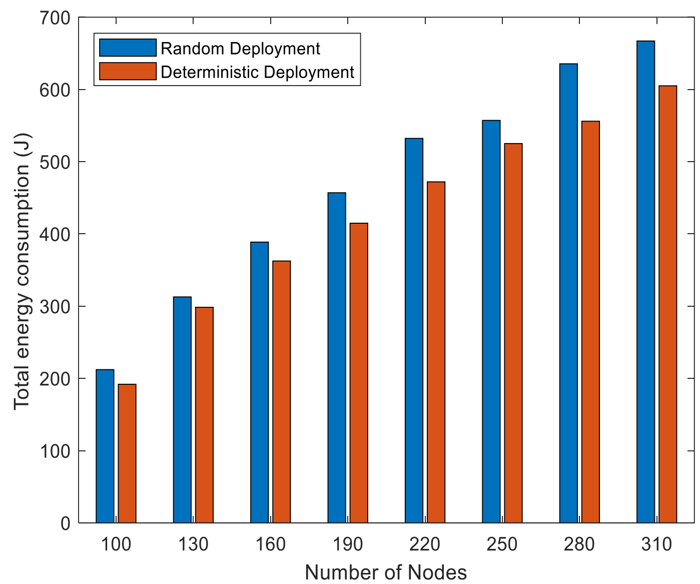


Figure 5-17: Impact of Sinks Deployment Strategy on EEDOR Total Energy Consumption

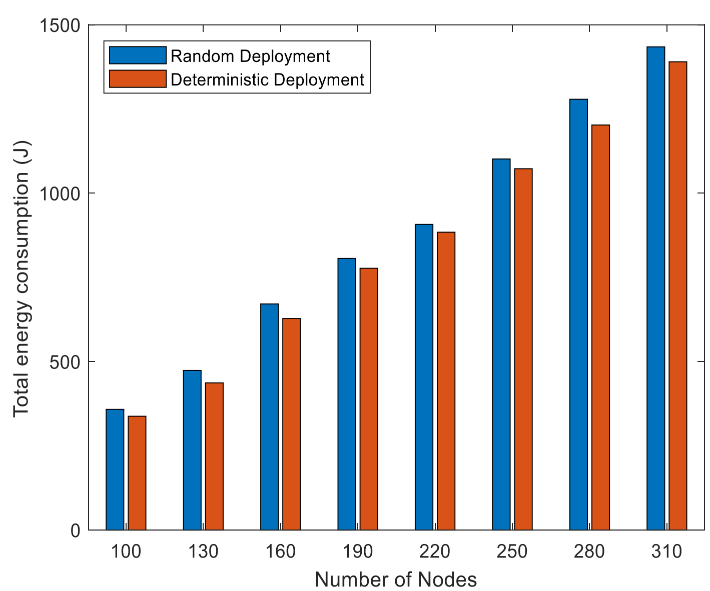


Figure 5-18: Impact of Sinks Deployment Strategy on EEDOR-VA Total Energy Consumption

As in scenario #1, Figure 5-19 shows that deterministic sink deployment results in a higher PDR than random sink deployment. Moreover, the PDR of EEDOR-VA is illustrated in Figure 5-20, which shows that, the deployment strategies have very little effect on the PDR of EEDOR-VA. This is expected as in scenario # 1.

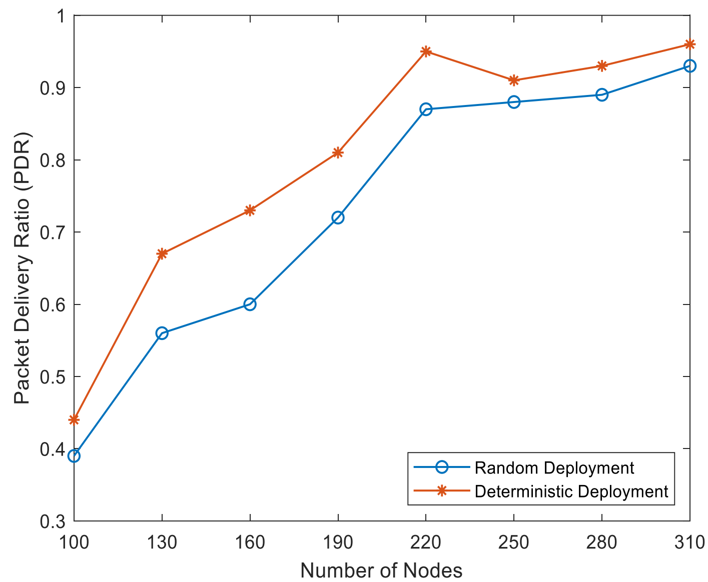


Figure 5-19: Impact of Sinks Deployment Strategy on EEDOR Packet Delivery Ratio

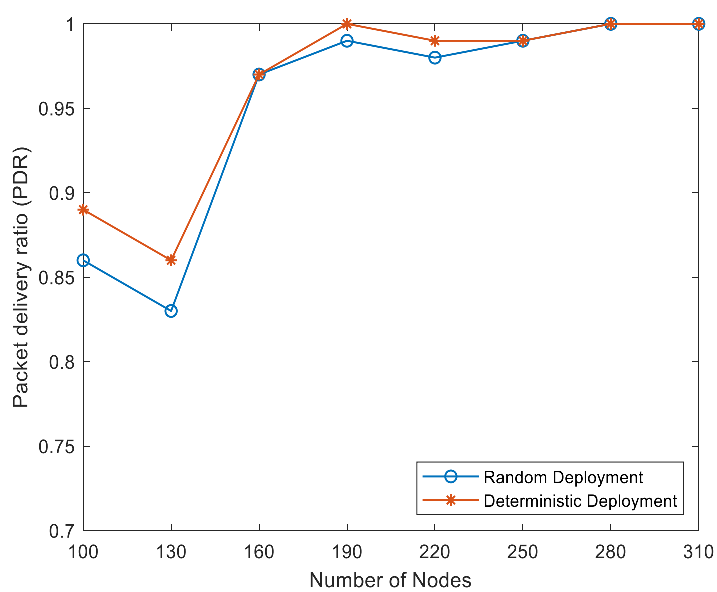


Figure 5-20: Impact of Sinks Deployment Strategy on EEDOR-VA Packet Delivery Ratio

5.4 Conclusions

In this chapter, we discussed the major sink topologies in UWSNs. We reviewed the UWSNs topologies based on number of sinks (i.e. single-sink and multi-sinks networks) as well as sink deployment strategies (i.e. random and deterministic). Further, we evaluated the two proposed routing protocols EEDOR and EEDOR-VA considering single-sink vs. multi-sinks UWSN topologies as well as two different sink deployment strategies and we analyzed the influence of theses topologies and deployments on the routing performance in terms of energy usage and PDR. Simulation results showed the benefits and drawbacks of each sink topologies and deployments on the routing protocols performance. Utilizing the multi-sinks and deterministic deployment both lead to energy conservation in the UWSNs and increased PDR.

Chapter 6 **Conclusion and Future Directions**

In this chapter, research in UWSNs is overviewed, unique contributions of this thesis are summarized and directions for future work are discussed. This chapter is arranged as follows: the topic of this thesis is summarized in Section 6.1. Then the contributions achieved by this research work are presented in Section 6.2. Finally, the directions for future work related to this thesis area of research are outlined in Section 6.3.

6.1 Overview

In this thesis, we introduced preliminary concepts of Underwater Sensor Networks (UWSNs) and the acoustic communication channel. We outlined the most challenging characteristics of the underwater environment that must be considered when creating or developing routing protocols. We also discussed the opportunistic routing (OR) technique, presented its components in detail and explained the concept of geographic-based and depth-based OR protocols. Moreover, we presented a summary of the state-of-the-art related to our research topic.

Based on the aforementioned research presented in this thesis, we concluded that one of the most difficult issues in UWSNs is the energy efficiency since high power is required for acoustic transmission. So far, underwater sensor nodes are battery operated devices, and their batteries are restricted, difficult to replace and cannot be recharged owing to the harsh and inaccessible deployment environment. Another important issue in UWSNs is the void area that can block the communication between two or more network components and influence the performance of the network. Our effort in this thesis focused on exploring these two issues and developing routing protocols that use the OR technique to manage energy conservation and the void area problems. The proposed protocols are depth-based routing protocols that do not need knowledge of the full dimensional location information and do not require the complicated routing table maintenance. In our proposals, the request/reply messages sizes were kept as small as possible to minimize the routing overhead, since the available bandwidth of the acoustic channel in the UWSNs is extremely low. Moreover, the robustness of the proposed protocols was improved by using the hop-by-hop structure, which allowed relay nodes to adapt more effectively to quick changes caused by the nature of UWSNs and/or the underwater environment.

Through this work, we simulated our proposed protocols using MATLAB to study their behavior and performance. We did an extensive simulation experiment to examine the performance of the proposed protocols compared to existing protocols. Then, we considered the number of surface sinks and deployment strategy and examined their influence on sink connectivity and void nodes.

6.2 Summary of Contributions

First, we tackled the problem of energy depletion in UWSNs. We designed a novel energy efficient routing protocol called EEDOR. The proposed protocol applies OR techniques to minimize the overall energy dissipation and enhance the performance of the UWSNs. EEDOR was built based on a simple design that allows sensor nodes to form their forwarding set by only exchanging their local information when they have a packet to forward. The forwarding set formed by sensor nodes are based on exchanged information collected locally by only listening to the FwdReq/FwdRep messages. Through an extensive simulation experiment, the performance of the EEDOR was evaluated and compared to other similar depth-based protocols including DBR, EEDBR, EECOR and FLCOR. EEDOR was shown to outperform all other techniques in energy conservation and provide a significant increase in network lifetime.

Our second major contribution is the EEDOR-VA routing protocol, a novel Energy Efficient Depth-based Opportunistic Routing with Void Avoidance for UWSNs. Motivated to maintain a low energy consumption while supporting a high PDR, the EEDOR-VA protocol uses a hop-count discovery processes to determine if a route exists between source and sink(s), which guarantees data packet delivery. Moreover, a unicast HCREP technique utilized by relay nodes conserves sensor node energy and minimizes overall energy depletion by decreasing the number of nodes that will forward the HCREP messages. The simulation results showed that EEDOR-VA achieves a much more balanced energy dissipation when compared to DBR and outperforms EEDOR and DBR in terms of PDR.

The third contribution involved the examination of UWSN architectures with consideration of the number of sink(s) and their deployment strategy. Motivated by increasing the connection between underwater sensor nodes and sink(s) to minimize the energy consumption in the transmissions between the source and sink(s), UWSNs using single-sink vs. multi-sinks and random vs deterministic sink deployment strategies were implemented. The simulation results show that a deterministic multi-sinks strategy can balance the distribution of the data forwarding load between relay nodes, especially in the first layer near the surface, and greatly reduce the forwarding requests and reply overhead.

6.3 Future Research Directions

A description of several research subjects that could be followed in the future as an extension of the routing protocols given in this thesis may be found in the list below:

- In the proposed routing schemes, the deployed underwater sensor nodes and surface sink(s) are assumed to be static. Therefore, we did not consider sink and node mobility in our proposed schemes. As a future work, mobility of sensor (especially horizontal movement due to water current) and/or sink(s) could be considered to investigate its impact on the performance of the proposed schemes.
- For future work, the experiments of proposed routing protocols could be implemented in the two-dimensional scenarios since this scenario is also common in UWSNs beside the three-dimensional scenarios.
- Energy efficiency and energy consumption balancing could be researched further. Node energy as a primary parameter for sorting the forwarding set candidates and assigning rank could be investigated. Also the impact on network lifetime of various forwarding set node selection criteria could be further investigated.
- Fuzzy Logic Inference (FLI) could be implemented to optimize the membership function of the forwarding set candidates. By integrating more than one of the networks and/or sensor node characters in the forwarding set formation phase the overall suitable nodes will be chosen as forwarding candidates. This approach

may help in rotating the priority between forwarding candidates and gain more energy consumption balancing.

- The void areas problem affects sparse networks the most. However, dense networks also could suffer from void areas due to sensor node random distribution and mobility. An enhanced energy balancing routing protocol that takes into consideration 2D and 3D architectures might mitigate void areas that can be caused by energy holes in dense UWSNs.
- The hidden node problem is another important issue that can affect the overall network performance, increasing energy usage due to duplicate transmissions and increasing packet loss due to overhead and collisions. Our proposed protocols would benefit from a mechanism to oversee this issue. For future work, delivering end-to-end ACKs or controlling the forwarding set candidates by adapting factors such as the forwarding area and the depth threshold or energy level could be utilized to address this problem. Moreover, providing a comparison analysis of network performance when using these different factors could help other researchers.
- Delay caused by void nodes is addressed with our EEDOR-VA the void avoidance proposal protocol. However, the overall end-to-end delay is considered as a trade of with the energy conservation and it requires more investigation to joint optimization of energy consumption and delay.
- Due to the high cost of the underwater sensor nodes, sparse networks are more common and more likely to suffer from void areas. However, optimizing the number of deployed nodes and/or sinks is another future direction that could be

consider in order to optimize the networks performance and leads to reduced economic losses.

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