

Performance Evaluation of Opportunistic Routing Protocols for Multi-hop Wireless Networks

by

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Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
For the M.A.Sc. degree in
Electrical and Computer Engineering

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Abstract

Nowadays, Opportunistic Routing (OR) is widely considered to be the most important paradigm for Multi-hop wireless networks (MWNs). It exploits the broadcast nature of wireless medium to propagate information from one point to another within the network. In OR scheme, when a node has new information to share, it first needs to set its forwarding list which include the IDs and/or any relevant information to its best suited neighboring nodes. This operation is supported by the use of appropriate metrics. Then, it executes a coordination algorithm allowing transmission reliability and high throughput among the next-hop forwarders. In this paper, we provide a comprehensive guide to understand the characteristics and challenges faced in the area of opportunistic routing protocols in MWNs.

Moreover, since the planet we live on is largely covered by water, OR protocols have gained much attention during the last decade in real-time aquatic applications, such as oil/chemical spill monitoring, ocean resource management, anti-submarine missions and so on. One of the major problems in Underwater Wireless Sensor Network (UWSNs) is determining an efficient and reliable routing methodology between the source node and the destination node. Therefore, designing efficient and robust routing protocols for UWSNs became an attractive topic for researchers. This paper seeks to address in detail the key factors of underwater sensor network. Furthermore, it calls into question 5 state-of-the-art routing protocols proposed for UWSN: The Depth-Based Routing protocol (DBR), the Energy-Efficient Depth-Based Routing protocol (EEDBR), the Hydraulic-pressure-based anycast routing protocol (Hydrocast), the Geographic and opportunistic routing protocol with Depth Adjustment for mobile underwater sensor networks (GEDAR), and the Void-Aware Pressure Routing for underwater sensor networks (VAPR). Finally, it covers the performance of those protocol through the use of the R programming language.

Sommaire

De nos jours, le routage opportuniste (OR) est considéré comme étant le plus important paradigme destiné aux réseaux sans fils à multi-bonds (MWNs). Il prend avantage de la manière intrinsèque dont se propage les ondes dans les réseaux sans fils afin d'assurer la transmission des données à l'intérieur d'un réseau sans fils quelconque. Dans un système OR, lorsqu'un nœud veut partager une information avec son voisinage, il procède comme suit : en premier lieu, il établit une liste structurée selon une certaine métrique qui contient l'identifiant des nœuds les plus favorables ainsi que n'importe quelles autres informations jugées nécessaires. En second lieu, il assure la coordination de la transmission des paquets de données des nœuds voisins sélectionnés à l'aide d'un algorithme dédié. Dans ce document, nous proposons une étude approfondie qui permet de comprendre les caractéristiques des protocoles de routage opportuniste ainsi que les différents défis auxquels ils font face dans un MWNs.

De plus, vu que la planète est en grande partie composée d'eau, beaucoup se sont intéressés aux applications potentielles des réseaux opportunistes dans le milieu sous-marin (ex : contrôle de la qualité des eaux, gestion des ressources aquatiques, sécurité des régions côtières.). Cependant, l'un des plus grands problèmes que confrontent les réseaux sans fils sous-marins se révèlent être l'établissement d'un processus efficace et viable pour la transmission des données entre les nœuds composants le réseau. Pour cela, une communauté grandissante de chercheurs et chercheuses s'est dévouée à la conception de protocoles de routage opportuniste stable, efficace et robuste. Dans ce document, nous tenterons de définir et les facteurs déterminant d'un réseau de capteurs sans fils sous-marin (UWSN). De plus, notre analyse sera soutenue par la description détaillée de 5 des protocoles les plus importants dans le domaine à savoir : *The Depth-Based Routing protocol (DBR)*, *the Energy-Efficient Depth-Based Routing protocol (EEDBR)*, *the Hydraulic-pressure-based anycast routing protocol (Hydrocast)*, *the Geographic and opportunistic routing protocol with Depth Adjustment for mobile underwater sensor networks (GEDAR)*, and *the Void-Aware Pressure Routing for underwater sensor networks (VAPR)*. L'évaluation expérimentale de ces protocoles à l'aide de l'outil de simulation R sera aussi présentée.

Acknowledgements

I would like to express my deep gratitude to Professor Azzedine Boukerche, my thesis advisor, for his patient guidance, enthusiastic encouragement and useful critics of this research. Moreover, without his financial support this work would have never been possible. I am particularly grateful for the assistance given by Dr. Rodolfo Wanderson Lima Coutinho for his constructive feedback and assistance in keeping my progress on the right path.

My grateful thanks are also extended to all members of the PARADISE Research Lab for their support in offering me useful advices and resources to complete this thesis.

I also want to thank all of whom in one way or another contributed in the completion of this paper.

Last but not the least, I must express my very profound gratitude to my parents for providing me with unconditional support and continuous encouragement throughout my study and through the process of this research.

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List of Abbreviations

<i>ACK</i>	Acknowledgment
<i>AODV</i>	Ad hoc On-Demand Distance Vector Routing
<i>AWGN</i>	Additive White Gaussian Noise
<i>BGP</i>	Border Gateway Protocol
<i>BPSK</i>	Binary Phase Shift Keying
<i>CDMA</i>	Code Division Multiple Access
<i>CODEB</i>	Network Coding-Based Broadcast in Mobile Ad-hoc Networks
<i>CORE</i>	A Coding-aware opportunistic routing mechanism for wireless mesh networks
<i>CORMAN</i>	Cooperative Opportunistic Routing in Mobile Ad Hoc networks
<i>CS</i>	Candidate set selection
<i>CSA</i>	compressed slotted acknowledgment
<i>DBR</i>	Depth-Based Routing
<i>DIFS</i>	Distributed Inter Frame Space
<i>DP</i>	Distance Progress
<i>DSDV</i>	Destination Sequence Distance Vector
<i>DSR</i>	Dynamic Source Routing
<i>DUAL</i>	Diffusing Update Algorithm
<i>EAX</i>	Expected Any-path Transmission
<i>EDC</i>	Estimated Duty Cycle wake-ups
<i>EDP</i>	Expected Distance Progress
<i>EEDBR</i>	Energy-Efficient Depth-Based Routing
<i>EEOR</i>	Energy-Efficient Opportunistic Routing in Wireless Sensor Networks
<i>EIGRP</i>	Enhanced Interior Gateway Protocol
<i>ENS_OR</i>	Energy Saving via Opportunistic Routing
<i>EOT</i>	Expected One-hop Throughput
<i>EOTX</i>	Expected Opportunistic Transmission Count
<i>EPA</i>	Expected Packet Advancement
<i>ETT</i>	Expected Transmission Time
<i>ETX</i>	Expected Transmission Count

<i>ExNT</i>	Expected number of transmission
<i>ExOR</i>	Extremely Opportunistic Routing
<i>FSA</i>	Fast Slotted Acknowledgment
<i>GEDAR</i>	Geographic and opportunistic routing protocol with Depth Adjustment
<i>GeRaF</i>	Geographic Random Forwarding
<i>HiBOp</i>	History Based Opportunistic routing protocol
<i>hop_cnt</i>	Hop-Count
<i>Hydrocast</i>	Hydraulic-pressure-based anycast routing protocol
<i>IS-IS</i>	Intermediate System to Intermediate System
<i>LAR</i>	Location Aided Routing
<i>MAC</i>	Medium Access Control
<i>MANET</i>	Mobile Ad hoc NETworks
<i>MORE</i>	MAC-independent Opportunistic Routing and Encoding protocol
<i>MWN</i>	Multi-hop Wireless Network
<i>MWN</i>	multi-hop wireless network
<i>NADV</i>	Normalized Advancement
<i>NAV</i>	Network Allocation Vector
<i>NC</i>	Network Coding
<i>OAPF</i>	Opportunistic Any-Path Forwarding
<i>OEC</i>	Opportunistic End-to-end Cost
<i>OEOT</i>	Opportunistic Effective One-hop Throughput
<i>OETT</i>	Opportunistic Expected Transmission Time
<i>OLSR</i>	Optimized Link State Routing Protocol
<i>ONC</i>	Opportunistic Network Coding for Wireless Networks
<i>OPRAH</i>	Opportunistic Routing in dynamic Ad Hoc networks
<i>OpRENU</i>	Opportunistic Residual Expected Network Utilities
<i>OR</i>	Opportunistic Routing
<i>OR</i>	Opportunistic Routing
<i>OSPF</i>	Open Shortest Path First

<i>PDP</i>	Partial Dominant Pruning
<i>PDR</i>	packet delivery ratio
<i>PSR</i>	Proactive Source Routing
<i>QoS</i>	Quality of Service
<i>RACK</i>	Robust acknowledgment
<i>RF</i>	Radio Frequency
<i>RIP</i>	Routing Information Protocol
<i>RSSI</i>	Received Signal Strength Indicator
<i>RTS-CTS</i>	Request To Send/ Clear To Send
<i>SenseCode</i>	Network Coding for Reliable Sensor Networks
<i>SIFS</i>	Short Interframe Space
<i>SNR</i>	Signal-to-Noise Ratio
<i>SOAR</i>	Simple Opportunistic Adaptive Routing protocol
<i>src</i>	source
<i>TR</i>	traditional routing
<i>UASN</i>	Underwater Acoustic Sensor Network
<i>UWSN</i>	Underwater Wireless Sensor Network
<i>VAPR</i>	Void-Aware Pressure Routing
<i>WMN</i>	Wireless Mesh Networks
<i>WSN</i>	Wireless Sensor Networks

Chapter 1

Introduction

For the past years Opportunistic Routing (OR) has been among the most commonly investigated type of routing techniques in the networking field. Most studies tend to focus on the challenges, issues, classifications, performances, and applications of OR in different operation milieu. However, with the proliferation of papers that claim to address the different challenges in the OR network, a comparative study is in order. In this chapter, we introduce the background of Opportunistic Routing (OR) in multi-hop wireless network. Then we explain the motivation for conducting this study. Furthermore, we present the objectives and contributions of our research. Ultimately, we draw the thesis outlined in the concluding section.

1.1 Motivation

A network is carefully designed structure that fosters the transmission and reception of information. And also, the sharing of resources among devices within a given domain. Traditionally, the devices emulate a wired configuration and often involve multiple network adapters and routers that connect to each other. In that case, to cover a vast area with various endpoints, a wired network requires a considerable amount of equipment such as cables and switches. Additionally, to prevent disruption, the cables must be laid on an area where they are less exposed to deterioration. The needs for larger network coverage and the

widespread usage of mobile devices prove to be a critical factor in the adoption of wireless network scheme. In contrast to the wired network where the information or resources are shared through a predefined physical link; wireless network offers more flexibility and versatility by embracing the opportunistic behavior of the wireless channel to guarantee the exchange of data.

Within this framework, Opportunistic routing is recognized as being the most promising routing approach for wireless multi-hop networks. The fundamental idea of OR is overhearing neighboring nodes data packets transmission and forward them in a controlled manner towards an intended destination. Thus, OR approach offers a viable option to deal with unreliable wireless links by dynamically selecting multiple routes to reach a gateway node, and consequently, increase the packet delivery ratio. Furthermore, OR broadcasting nature is exploited to cope with unpredictable and unstable topologies, prolonged disconnections, and partitions that occurs in a challenged wireless environment [2]. Therefore, OR technique can be applied to all type of wireless multi-hop networks, like wireless mesh networks (WMNs), wireless sensor networks (WSNs) and mobile ad hoc networks (MANETs) [3].

Until now the applications of OR techniques have been widely addressed [4, 5, 6, 7] for terrestrial multi-hop routing networks. They aim to improve network throughput, energy efficiency, wireless link quality, and latency. The vast majority of these studies can be tested experimentally to corroborate their theoretical analysis and simulation results. The successful implementations of several OR protocols in terrestrial network attract growing interest in their applications/adaptation to the submarine habitat. Hence, many researchers [8, 9, 10, 11] have examined the principal challenges and benefits of such techniques in a harsh environment like the oceans.

Contrary to terrestrial wireless networks (TWNs) frequently considered as a two dimensional space, the underwater wireless sensor networks (UWSNs) represent a volume where nodes can move in without following any mobility pattern [1]. A further key distinction is the communication channel used in each scenario. UWSNs use acoustic waves ($1.5 \times 10^3 m/s$) while TWNs adopt the radio waves ($3 \times 10^8 m/s$). Therefore, it is more complex to design routing protocols dedicated to underwater sensor networks than terrestrial

wireless networks.

In this thesis, our objectives are to provide a comprehensive guide to understand the characteristics and challenges faced in the area of opportunistic routing protocols as well as to design robust and scalable OR protocols. Explicitly, we intend to present a thorough analysis of the OR considering various scenarios such as WMNs, WSNs, and MANETs. We will analyze various protocols related to the topic in order to understand the potentials and drawbacks of OR. In addition, we plan to proceed with the implementation of five state-of-the-art routing protocols designed for UWSNs in order to evaluate their performances.

1.2 Contributions

Our paper consists of a literature review of opportunistic routing concept and the performance evaluation of OR protocols for vehicular networks. Specifically, we provide an in-depth analysis of DBR [12], EEDBR [13], Hydrocast [14], GEDAR [10], and VAPR [15] protocols. These protocols present unique characteristics and inspire the development of various other protocols. The aforementioned contributions include:

- **Classification of opportunistic routing components.** To grasp the fundamentals of opportunistic routing which is essential to define its components and outline their respective roles in the evaluation of network performance.
- **Scientific survey and classification of fifteen well-known routing protocols.** To provide an overview of the current state of the studies of OR in multi-hop networks we will investigate fifteen of the most cited papers. We will also classify them based on the metric used, the candidate set selection and the candidate coordination methodology, the stated objective, and the MWNs model.
- **Implementation of five state-of-the-art UWSNs protocols using R.** To the best of our knowledge, this study is the first routing protocol implementation using RStudio as the simulation tool. The results showed this software provides sufficient resources to conduct extensive simulations when developing routing protocols.

- **Introduction of new metrics for OR protocols performance evaluation.**

The earlier mentioned protocols are submitted to an extensive set of simulation and assessed according to the five metrics described in [4.2](#).

1.3 Thesis Outline

This thesis is comprised of 5 chapters and structured as follows:

- Chapter [2](#) provides a comprehensive scientific literature review of routing techniques. Moreover, we introduce the applications of opportunistic routing in diverse type of multi-hop wireless networks. In closing, we survey and classify fifteen OR routing protocols in MWNs.
- Chapter [3](#) proposes an exhaustive study of opportunistic routing in underwater sensor networks. We also outline the importance of developing energy efficient, scalable, and reliable routing protocols to confront challenges of the underwater environment. Finally, we describe in details five state-of-the-art protocols designed for UWSNs.
- Chapter [4](#) argues the simulation parameters and explains the graphs that summarize the performance analysis of each implemented protocol.
- Chapter [5](#) recapitulates the key aspects addressed in this thesis. The chapter also explores possible research directions for future works.

Chapter 2

Related Work

In this Chapter, we analyze the critical concepts behind opportunistic routing protocols and their applications in multi-hop wireless networks (MWNs). In Section 2.1 and 2.2 we present the fundamentals concept of routing protocols and their classifications. In Section 2.3 to 2.6, we discuss in great details the key elements, i.e., the metrics, the candidate set selection, and the candidate coordination methodologies. Section 2.7 primarily focuses on the analysis of some major state-of-the-art OR-based protocols. Ultimately, we provide key information that encompasses the entire chapter.

2.1 Routing in a Nutshell

Before getting into specifics we will give a slight overview of routing protocols. A routing protocol is a set of rules governing the process of moving a packet of data from a source toward their intended destinations [16]. It uses software and routing algorithms to optimize the exchange of data between nodes and report changes with the other entities within the network in order to update their database system. Therefore, the network will be able to react to changes by adjusting dynamically the advertisement interval considering its conditions (e.g., changes in network topology and traffic patterns), thereby routing decisions do not have to be predetermined and static. The major operations a routing protocol completes can be categorized into three different functions known as discovery,

route management, and path determination.

- The discovery function goal is to identify the routers within the network.
- The route control purpose in a network is to keep track of all possible sequences of intermediate nodes from a source node to a destination node for network messages.
- The path determination addresses the selection of the best free loop path in the network to send data packets to any given destination.

Based on the operational characteristics of data distribution the process to be followed to perform this data processing is divided into three main algorithms, respectively: Link-state, distance-vector and path vector.

The link-state algorithm, rely on each router in the network to advertise the state of each of their links to every other router within the local routing domain [17]; therefore, each node in the network has a broad knowledge of the entire network topology. Typically, a node ruled by the link-state algorithm, send an update message to its neighboring nodes only when there is a change in the topology. Examples of Link-state routing protocols include the Open Shortest Path First (OSPF) [18] and the Intermediate System to Intermediate System (IS-IS) [19].

Nodes running distance-vector algorithms advertise the vector (path) and distance (metric) for each destination reachable within the network to adjacent peers [17]. Distance is usually measured in hops, though the distance metric could be an end-to-end delay, packet loss, or something similar. Upon reception of routing information from a source, the receiving node updates its own cost to a given destination using that neighbor as a link. Also, it engages the path selection process to determine which path offers the best option to progress toward the destination. Bellman-Ford algorithm and Diffusing Update Algorithm (DUAL) are among the most widely used path selection procedures for the distance-vector algorithm. Two representatives of this category are the Routing Information Protocol (RIP and RIPv2) [20] and the Enhanced Interior Gateway Protocol (EIGRP) [21].

While the first two algorithms are dedicated to the intra-domain routing protocol, the path-vector belongs to the inter-domain group. In path-vector algorithms, a source node does not rely on the cost of reaching a given destination to determine whether each path available is loop-free or not [2]. When a neighboring node receives the routing table from a source node, it adds its own address to the path and validates the loop-free path before broadcasting the resulted routing table in its turn. Hence, a path-vector algorithm guarantees loop-free paths through the network by recording each hop the routing advertisement traverses through the network. The main protocol that uses the path-vector approach is called Border Gateway Protocol (BGP).

Another critical operation of a routing protocol is to defend the network against malicious nodes that threaten the security and/or anonymity of the exchanged data. Encryption cannot fully protect the data communicated between nodes, as routing information may expose the identities of the communicating nodes and put their relationships at risk. Various studies, [22, 23, 24, 25, 26], have presented protocols that incorporate a mechanism to establish trust among mobile nodes within a network. Typically, they consider the nodes forwarding behaviour and their trust level while avoiding untrustworthy nodes during the forwarding process. Further discussion of this aspect of the routing protocols falls outside the scope of this paper.

2.2 Classification of Routing Protocols

Some preliminary work has been carried out in the literature regarding the different methodologies employed to propagate data through a network [27, 28, 29, 30, 31]. There are two different routing protocol classes, namely: The traditional routing protocol and the opportunistic routing. The traditional routing is beyond the scope of this text and so will be discussed briefly.

The fundamental of Traditional Routing (TR) consists of the transmission of a data packet from a sender node to a single next-hop candidate (receiver node) using a unicast transfer mode i.e. a communication technique that involves a single sender and a single

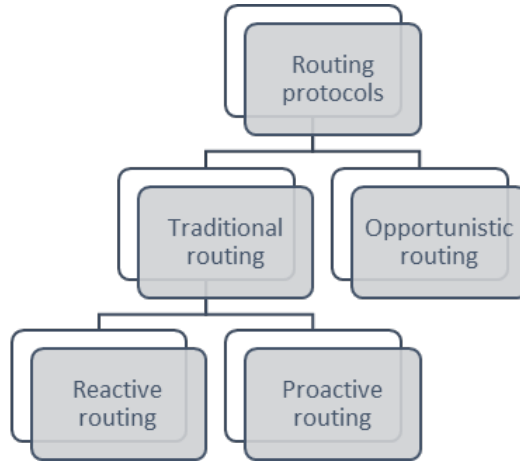


Figure 2.1: Different type of routing protocols

receiver over a network. TR schemes consider wireless links as a point-to-point wired link and do not utilize the broadcasting nature of the wireless medium [32]. In the event where the receiver node did not receive the packet after a certain amount of attempts, the data packet gets discarded. Moreover, traditional routing requires the establishment and maintenance of end-to-end routing paths. Based on the stability of the network infrastructure under varying network dynamics this class of protocol falls into two categories: reactive and proactive.

In reactive routing protocols also known as on-demand routing, a node only initiates a route discovery process through the network upon the reception of a request to route a packet to a specific destination. Typically, to establish that route it employs a global search strategy (e.g., flooding) [33]. Once a route has been established, it is maintained by a route maintenance process until either the destination becomes inaccessible along every path from the source or until the route is no longer desired [34]. Therefore, they reduce the overheads in any given network at the cost of latency due to route determination. Routing protocols such as Ad hoc On-Demand Distance Vector Routing (AODV) [35], Dynamic Source Routing (DSR) [36], and Location-Aided Routing (LAR) [37] are some popular example of reactive protocols.

On the other hand, proactive or table-driven routing protocols refer to a routing category where each node continuously advertises their routing state to every other node in

the network. Accordingly, all the nodes composing the network possess somehow a map of the entire topology. During the transmission of a data packet, there will not be any delay related to path research if a route has already existed. Otherwise, the packets will be stored so as to be retrievable in order of reception until the path toward the destination is completed. In contrast to reactive routing protocols, proactive schemes (mostly in high-density network) offer very low latency but require a sheer amount of resources such as memory space, battery life, buffer, etc. to keep routing information up-to-date. Some examples of proactive routing protocols are Destination-Sequence Distance Vector (DSDV) [38], Randomized Destination-Sequenced Distance Vector (R-DSDV) [39], and Optimized Link State Routing Protocol (OLSR) [40].

Over the last decades, Opportunistic Routing (OR) protocol has received much attention from researchers because it could be used as an alternative to improve the performance of Multi-hop Wireless Network (MWN). As reported in [32], in a wireless environment where transmission failures occur frequently, the transmission of a packet can be made through any possible link rather than any prefixed link, using OR schema. In contrast to the traditional routing, OR is a fairly new paradigm for mobile wireless networks that involve a subset of neighboring nodes as the next-hop forwarding candidates instead of a single node [41]. The neighbors are arranged in an orderly fashion so that when they received a data packet from the associated source node the broadcasting starts with the nodes offering the best advancement probability to reach the final destination. Hence, OR schema helps to reduce the probability of transmission failure which in turns reduces the energy cost of retransmission [32]. In the literature, the previously mentioned set of neighbors is generally known as the Candidate Set (CS) and the prioritization process as the Candidate Coordination (CC). Also, it is important that each node must be equipped with minimum computing faculty to make forwarding decisions.

The example shown in Figure 2.2 illustrates how TR and OR works. Node A represents the packet transmission starting point (source), node D is the ending point (destination), and B, C are intermediate nodes through which packet can be transmitted to the final destination. Typically, if we use traditional routing for this scenario, with the straight arrows

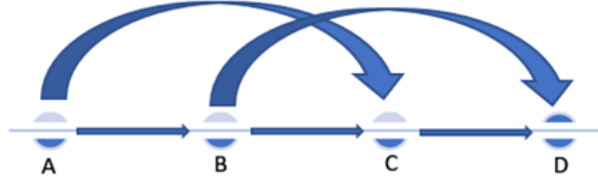


Figure 2.2: Routing protocols in MWNs

depicting the pre-establish path, the transmission sequence would be A, B, C, D . Considering the curved arrows as the communications range of the nodes, Figure 2.2 shows clearly that node A can communicate directly with node C , and B with node D . However, TR is designed in such a way that overhead packets are automatically ignored. Consequently, when node A sends a packet, although nodes B and C will receive it only B will be selected as the next-hop forwarder. Then, if the packet gets stuck for any reason at node B , it will be dropped and therefore generate a packet loss. Now, let us consider the case where the OR scheme is applied in the network. Nodes B and C formed the candidate set of source node A when the latter sends a packet in destination of node D . Assuming that all the nodes in the CS received the data packet correctly, based on the CC metric used (here, it is the minimum number of transmissions), in order to reach node D , the nodes closer to the final destination will be selected, namely: node C . Thus, the path for this scenario will be composed of nodes A, C, D . If nodes C fails to receive the packet, then node B will be authorized to transmit it using the same principle we just mentioned. Resulting from it is the new path sequence A, B, D . Therefore, by using OR and by decreasing the number of transmissions, the throughput of the network is improved and network resources are saved [16].

Table 2.1 summarizes the differences between opportunistic routing and traditional routing schemes based mainly on the selection mechanism of the next-hop forwarders and whether or not they are taking advantage of the broadcast nature of the wireless medium. In the next sections, we present a thorough analysis of the opportunistic routing which includes the opportunistic routing components, the algorithms employed and applications of OR in different type of networks.

Table 2.1: Comparison between Opportunistic Routing and Traditional Routing schemes

	<i>Number of forwarder nodes</i>	<i>Data distribution</i>	<i>Overhead packets</i>	<i>Relay Selection</i>	<i>Knowledge of the topology</i>
TR	Single	Unicast	No	Fixed	Required
OR	Multiple	Broadcast	Yes	Dynamic	Not required

2.3 Review of Opportunistic Routing

A growing body of literature has identified three essential elements when it comes to opportunistic routing, specifically: the OR metrics, the candidate set selection, and the candidate coordination. OR metrics play an important role in the selection and prioritization of CSs since they transform both the protocol requirements as well as operational performance to numbers which can be compared. Candidate set selection helps to determine an ordered list of suitable neighboring nodes to forward the data packet relying on the selected metrics. As for candidate coordination, it employs an embedded mechanism that prevents nodes from transmitting randomly. The CC method used the priority number information to schedule packet transmission starting with the highest priority nodes to the node with lesser priority (if necessary). If the coordination between the candidates is done imperfectly, it may result in the sending of duplicate transmissions of packets by different candidates [16]. Further details are given in the next section.

2.4 Metrics in Opportunistic Routing

The main purpose of OR is to reduce the number of transmission required to deliver packets to a given destination, leading to a lower end-to-end delay, delay variations (jitter), and energy consumption [4]. Therefore, it is crucial to choose the appropriate metrics to estimate the cost to reach the destination node from any sender node in a given network. The more precise this step can be, the higher the network performance will be. Based on the information available in several studies, we selected some of the most commonly used OR metrics useful for assessing network performance. They can be divided into two

Table 2.2: Metrics variables

i	Random node in the network
d	Destination node
C_i	Ordered candidate set of node i
D	Distance between two nodes
p	Link delivery probability between two nodes

main groups: the local or hop-by-hop metrics and the global or end-to-end metrics. The following abbreviated expressions are used to represent the technical facts that we will encounter in the next two subsections:

2.4.1 Hop-by-hop OR Metrics

Regarding the use of the hop-by-hop metrics, it requires that the sender node has the knowledge about how to transmit a data packet to its eligible immediate neighbors i.e. the next-hops. Thus, the hop-by-hop metrics helps to select and prioritize the next-hop forwarders based on the local information or the neighbors link properties. Some of the major hop-by-hop metrics are discussed in the next paragraphs.

The Distance Progress (DP) can be calculated by having the geographical distance between each neighbor and the destination [42]. It is reported in [16] that the use of DP is limited to a scenario where each node can select as many candidates as possible. Otherwise, the delivery ratio will be deeply affected as the sender node might select only the candidates that are closer to the destination and thus with weaker wireless links. Its expression is:

$$DP_{C_i}^{i,d} = D_{i,d} - D_{C_i,d} \quad (2.1)$$

The Expected Distance Progress (EDP) is the average distance advancement of a broadcasted packet taking advantage of the candidates set $C^{i,d} = \{c_1, c_2, \dots, c_n\}$ (with c_1 the node with the highest priority and c_n the lowest one) and the link quality between the

pair on nodes involved. Note that upon a packet transmission, the higher the EDP, the higher is the expected approach of the packet to the destination [43]. Its formula is given in equation 2.2.

$$EDP(i, d, C^{i,d}) = \sum_{i=1}^n DP_{c_i}^{i,d} \times p_{i,c_i} \prod_{j=1}^{i-1} (1 - p_{i,c_j}) \quad (2.2)$$

Expected One-hop Throughput (EOT) is a local metric that has been proposed in [3] for routing based on geographic distance. This metric was modified later to be compatible with multi-rate transmission and was renamed Opportunistic Effective One-hop Throughput (OEOT) [44]. Its main goal is to capture the trade-off between one-hop packet advancement and its cost (forwarding time) and it is calculated by dividing the average advancement with the average time. The components of the equation are presented as follows:

$$OEOT(F_i) = L_{pl} \times \frac{\sum_{i=1}^r a_{j_i} p_{j_i} \times \prod_{w=0}^{i-1} \bar{p}_{j_w}}{t_r \bar{p} F_i + \sum_{i=1}^r t_i p_{j_i} \times \prod_{w=0}^{i-1} \bar{p}_{j_i}} \quad (2.3)$$

Where, F_i is an ordered subset of the candidate set of node i ; a_{j_i} represents the Euclidean distance between the sender and the destination minus the Euclidean distance between the sender's neighbor and the destination; p_{j_i} is the data packet reception ratio from the sender node to a node listed in its CS; t_i the total medium time needed for a packet forwarding from the sender to the i th forwarding candidate; And L_{pl} is the data payload.

2.4.2 End-to-end OR Metrics

Contrary to the hop-by-hop metrics, in a network where the end-to-end metrics are used, it is necessary that all the nodes within that network have a kind of map of the associated topology. Based on that information the source nodes will be able to select and order the CS. Therefore, the calculated metric for each node is dependent on the cost of the remaining path from the neighbors of a node to its destination [16]. The main metrics of this group are presented briefly in the subsequent lines.

Hop-Count (hop_cnt) or minimum hop-count is one of the first metrics. used in TR and that has been adapted to OR. It refers to the number of intermediate nodes through which data must travel starting from a source to a final destination. In order to reduce latency, the nodes with the minimum number of hops are chosen to forward the packet. This metric does not take into account the link quality parameters which can cause the selection of a node with a very low probability and consequently affect the path delivery ratio.

Expected Number of Transmissions (ExNT) is the most important metric in OR. It provides an understanding of the effort required for the successful delivery of a packet from a given source to a destination [45]. In this context, the *effort* describes the amount of consumed resources and time during each transmission attempt. The ExNT is based on the transition probabilities of the Markov model. For equation 2.4 and 2.5, the network is formed by N nodes that are allowed to retransmit K times and the number of transient states in the model is approximated by $(N - 1) \times (K + 1)$. In equation 2.4, $p[X = h]$ defines the probability of transitioning from a nonabsorbing state i to an absorbing state j in precisely h steps.

$$p[X = h] = Q^{h-1} \times \mathcal{R} \quad (2.4)$$

Where X is a random variable that contains the number of transitions; h the number of steps to reach the destination; Q represents the transition probabilities between the transient states; and R groups all the transition probabilities from the transient states to the absorbing states. Equation 2.5 represents the expected value of X from which the ExNt is obtained.

$$\begin{aligned} E[X] &= \frac{\sum_{h=1}^{\infty} (h \times p[X = h])}{p[X = 1] + p[X = 2] + \dots} \\ &= \frac{1 \times \mathcal{R} + 2Q \times \mathcal{R} + 3Q^2 \times \mathcal{R} + 4Q^3 \times \mathcal{R} + \dots}{\mathcal{R} + Q \times \mathcal{R} + Q^2 \times \mathcal{R} + Q^3 \times \mathcal{R} + \dots} \\ &= \frac{(\mathcal{I} - Q)^{-2} \times \mathcal{R}}{(\mathcal{I} - Q)^{-1} \times \mathcal{R}} = \frac{\mathcal{N}^2 \times \mathcal{R}}{\mathcal{N} \times \mathcal{R}}. \end{aligned} \quad (2.5)$$

Expected Transmission Count (ETX) is a unicast routing metric which aims to minimize transmission count. As its name suggests, ETX refers to the measure of the average number of data traffic (transmissions and retransmissions) necessary from a sender node to reach a specific destination. It has been generalized for OR network by Chachulski et al. in [46] and became **Expected Opportunistic Transmission Count (EOTX)**. It refers to the minimum number of opportunistic transmissions to deliver a packet to its destination. The EOTX to deliver a packet from node s to a destination d is expressed as:

$$EOTX(s) = d(s) = \begin{cases} 0, & i = d \\ 1 + \sum_{c_i} P_{c_i} \min_{c \in C_i} d(c), & otherwise \end{cases} \quad (2.6)$$

Where P_{C_i} represents the probability of at least one node in C_i correctly receives the packet broadcast by node s for one transmission, and $\min_{c \in C_i}$ the candidate that offers the minimum cost to relay the packet. In EOTX, node s is included in its CS, so that it also is a candidate forwarder.

Expected Transmission Time (ETT) [47] is a traditional metric that helps achieve high network throughput. For OR, in [3] the authors proposed an extension of ETT called **Opportunistic Expected Transmission Time (OETT)** that refers to the expected time to send a packet from node i to any next hop in its forwarding CS under a given rate.

$$OETT_i^{C_i} = \frac{L_{pkt}}{R_i P_{C_i}} \quad (2.7)$$

Where L_{pkt} is the packet size, R_i designates the data transmission rate at node i , and P_{C_i} has the same definition in equation.

Expected Any-path Transmission (EAX) is another routing metric that considers the effect of opportunistic routing in estimating the ExNT given the forwarding C_i and the packet delivery probabilities between the forwarders P_{C_i} . The recursive formula elaborated to represent this metric is given by:

$$EAX(C^{s,d}, s, d) = S(C^{s,d}, s, d) + Z(C^{s,d}, s, d) \quad (2.8)$$

Where the first term of the second member of the equation refers to the number of transmissions from the source node to its CS and the second one the number of transmissions from the CS to the destination. Due to the recursive nature of EAX formula, the cost of calculating EAX in a large network with a great number of candidates is very high [8].

Estimated Duty Cycle wake-ups (EDC) [48], is a dedicated OR metric that was introduced by Ghadimi et al. in 2012. To ensure long network lifetime, nodes in WSNs are frequently put in a deep sleep state. However, the vast majority of OR schemes does not take that fact into account and assume that nodes are always awake and can overhear transmission from neighboring nodes. In order to tackle that problem, EDC was designed to reduce radio duty-cycles and lead to loop-free topology. As a result, the network will show significant improvement in its lifetime and end-to-end delays. Equation 2.9 encompasses the fundamental features of OR and its implementation is described by the authors as an appealing balance between effectiveness in forwarder set selection and simplicity of protocol analysis [48].

$$\text{EDC}(i) = \frac{1}{\sum_{j \in F_i} p_{ij}} + \frac{\sum_{j \in F_i} p_{ij} \cdot \text{EDC}(j)}{\sum_{j \in F_i} p_{ij}} \quad (2.9)$$

The first term of the second member of the equation is an estimation of the average one-hop forwarding delay while the second one strives to approximate the essential features of the subsequent delay from forwarders to the final destination.

Opportunistic Residual Expected Network Utilities (OpRENU) [49] utilizes a new approach to track the performance of a network. Instead of considering the widely used parameters such as the wireless link quality, the localization, or the number of hops, OpRENU takes into account the optimality of OR for utility based on a function of benefit and cost of transmission. In other words, when a packet successfully reaches its final destination, the utility of the delivery can be calculated as the difference between the benefit and the cost of transmission (2.10).

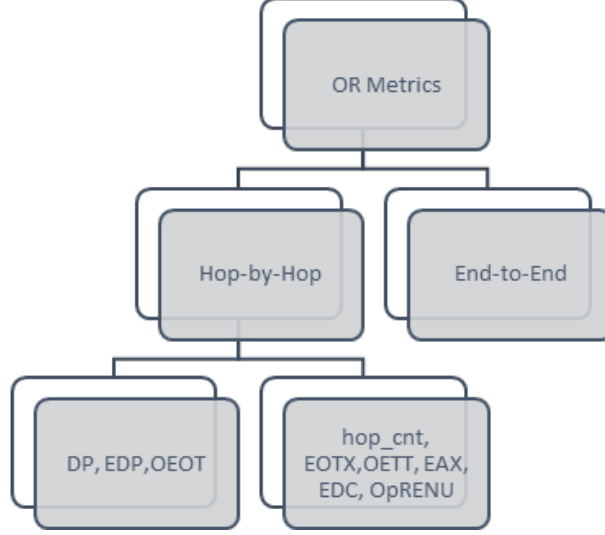


Figure 2.3: Summary of Opportunistic routing metrics

$$Opu_s^{C_{s,d}} = \sum_{i=1}^{|C_{s,d}|} (Opu_i^{C_{s,d}} \times p_{s,i} \prod_{j=1}^{i-1} (1 - p_{s,j})) - COST \quad (2.10)$$

Where $Opu_i^{C_{s,d}}$ is the OpRENU of node i used for the purpose of reaching destination d by using $C_{s,d}$, and $COST$ is the transmission cost at node s [16].

Figure 2.3 contains all the previously discuss metrics based on their category, specifically: local and global opportunistic routing metrics.

2.5 OR Candidate Set Selection

One of the most important components of the OR routing is the candidate set selection. It is the equivalent of the routing table in Traditional routing. During this phase, the goal is to choose the most suitable neighboring nodes as the next-hop forwarder. The metrics come into play when it comes to the prioritisation of the nodes surrounding a source node. Usually, in OR the parameters assessed are the energy consumption, the end-to-end delay, the number of nodes, wireless link quality. Based on the objectives, the choice of a particular metric constitutes a crucial step in OR scheme as they have a significant impact on a network performance. Moreover, to avoid high overhead in its

immediate neighborhood, a node must restrain the number of candidates it can select. In the literature, a considerable amount of studies divided CS into two main categories: Candidate prioritization, and candidate filtering [3].

2.5.1 Candidate Prioritization

Candidate prioritization is the process of arranging the candidate nodes in order of importance relative to each other. Initially, to achieve such a goal, a considerable number of metrics designed for TR were used in OR network (ex: DP, hop_cnt, ETT, ETX) with more or less success. In recent years, with the growing interest in OR schemes among researchers in the networking field, various TR metrics were extended to be compatible with OR networking environment (ex: EOTX, OETT, OEOT). Also, depending on the desired result, the metrics can be designed to handle different parameters whether it is the energy, the throughput, the number of hops or the cost to move a data packet from a source node to its final destination.

2.5.2 Candidate Filtering

Another component of the candidate set selection is the candidate filtering. Essentially, once all nodes in the candidate set are aware of their priority number; the next step is to remove the nodes that may deteriorate the network performance. By doing so, the number of packets overheard and duplicate transmission will be reduced significantly. The commonly used metrics for candidate filtering are presented in the following paragraphs.

Virtual link strength represents a logical link using the least cost path between a sender node and its targeted destination. It consists to combine the stronger links from the sender node to its candidate set so that the resulting link can achieve a higher packet delivery ratio (PDR). Based on the application when the virtual link strength reaches a certain threshold for the PDR (Ex: 85%) then the nodes can drop the remaining nodes in the candidate set. Therefore, it will relieve the local nodes from storing longer candidate list in the packet header and reduce the number of nodes involved in packet forwarding

mechanism. Assuming that all the candidates have the same PDR, the formula to calculate the PDR of the virtual link, VLS_{ci} , is given by:

$$VLS_{ci} = (1 - (1 - PDR_{node})^i) \quad (2.11)$$

In **candidate connectivity**, the goal is to avoid coordination failure between the nodes composing the same candidate set. Some preliminary work was carried out to describe a system where a source node will only select neighbors that can communicate with one another as the next hop forwarders [3]. For instance, when a node is localized within the communication range of a source node; if it cannot interact with all the other nodes in the candidate set it will be removed from the list of forwarders.

Duplicate probability refers to the operation by which the duplicate transmission probability of a candidate node is calculated. If the probability is higher than a threshold the candidate is dropped. It has been found that this technique is more accurate than other filtering approaches such as connectivity [3].

Pruning is used to remove the nodes with lesser contributions in the forwarding process. It helps improve a network performance by favoring proper allocation and use of network bandwidth and thus reduce unnecessarily flooded traffic.

2.6 OR Candidate Coordination

A key problem with much of the literature in relation to opportunistic routing is the candidate coordination methodology. The challenge here is to organize the nodes so as to enable them to transmit a packet towards a destination in an effective fashion. The usage of the CC allows the network to minimize redundant packet transmissions while choosing the paths that offer the least cost to forward a packet from one point to another [50]. It is worth mentioning that the candidate prioritization carries out an essential role in facilitating the CC to discover the most convenient route. In reference to the coordination technique used to manage packet transmission, the CC is classified into two major categories known as control-based and data-based candidate coordination [16].

2.6.1 Control-based Candidate Coordination

The fundamental of all control-based coordination approaches lies in the fact that all the nodes within the network area use control packet to share their most updated status. When a source node delivers a packet to its CS, the candidate nodes that have successfully received the packet reply to the sending node with a control packet as an of receipt. The control packet generated by the receiving nodes flows from those closer to the destination (higher priority) to those to the source. The next paragraphs outline two of the most commonly discussed control-based coordination approaches, namely: Acknowledgment-based and RTS-CTS coordination.

Acknowledgment-Based Coordination (ACK-based), introduce by Larsson in [51], is one of the most popular techniques used to ensure coordination between nodes within a network. Instead of selecting the next-hop forwarder prior to any data transmission, the ACK-based employ a methodology based on the reception of short acknowledgment packets from a previously ordered CS. In conformity with the acknowledgments received, the sender node determines the most suitable next-hop candidate.

Gaining popularity among researchers, the coordination model developed in [51] has inspired the authors of the Extremely Opportunistic Routing (ExOR) [30] to propose their own CC model. Figure 2.4 and Figure 2.5 show respectively the standard unicast MAC layer 802.11 and the modified version (ExOR frame) required to implement the coordination technique employed by ExOR. The presence of an ACK packet implies that a neighboring node has successfully received the packet. From the aforementioned figures, it can be inferred that the ACK message carries the ID information of the receiver node and some other critical information. As soon as these steps have been carried out, all the forwarding candidates must listen to all ACK slots to be able to decide the best forwarder candidate.

Figure 2.6 illustrates the acknowledgment-based coordination mechanism used in ExOR. In this example, the source *SRC* transmitted a packet to its CS composed by *Cand1*, *Cand2*, and *Cand3*. Upon reception of the packet, after a delay period of Short Interframe Space (SIFS) each node replies with an ACK packet. It results from our example that



Figure 2.4: Standard unicast 802.11 frame with ACK



Figure 2.5: ExOR frame with slotted ACKs

Cand2 cannot overhear the ACK packet of *Cand1*. In this case, we assume *Cand3* successfully receives the ACK of *Cand1*. If it is capable to interact with *Cand2*, it will notify this latter of the presence of a node with higher priority (i.e. *Cand1*). Therefore, *Cand1* will be the chosen node to forward the packet. A drawback of this method is the generation of duplicate packet transmission in the case where nodes with lower priority cannot hear any other higher priority ACKs.

In [52], the authors proposed a version of acknowledgment candidate coordination scheme called “compressed slotted acknowledgment” (CSA). It applies a similar acknowledgment scheme as the one used in ExOR. It also addresses the potential packet collision by introducing the channel sensing technique. The methods used can be described as follows: When a candidate with priority $i + 1$ fails to notice the ACK of a candidate with priority i from the same CS, it prematurely sends its ACK. In that case, it compresses the channel’s idle period so that it is smaller than the Distributed Inter Frame Space (DIFS). The

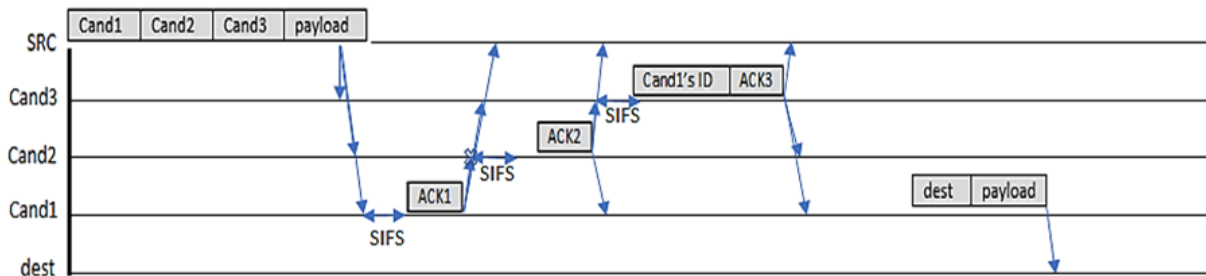


Figure 2.6: Acknowledgment-based coordination mechanism

Received Signal Strength Indicator (RSSI) occupies a critical role in determining whether or not the node with the higher priority has sent its ACK.

It has been found that latency and packet collision represent the key issues encountered in the coordination mechanism based on ACK. To handle those issues and improve the network performance, Yang et al. in [7] have presented the Fast Slotted Acknowledgment (FSA). It uses the channel sensing technique to confirm the successful reception of a packet by a suitable candidate and suppress other candidates from forwarding the same packet. In more details, FSA allows the highest priority node to send only one ACK upon reception of a packet. If the lower prioritized candidates received the packet, they constrain themselves from sending any ACK. Otherwise, the second highest priority candidate is authorized to transmit the packet. The packet transmission schedule is regulated as follows: For each node composing the CS of a given source node the delay in Equation 2.12 represents the amount of time it has to wait before deciding whether it should transmit ACK. After extensive simulations, the authors have shown that when compared to similar schemes, FSA can decrease the average end-to-end delay up to 50% in low-density network. FSA helps also increase a high-density network throughput to 20%.

$$T_{bTx} = T_{SIFS} + (n - 1) * T_{sensing_slot} \quad (2.12)$$

Where T_{bTx} represents the waiting time before a possible transmission, n the priority order of the candidate, T_{SIFS} the delay period of SIFS, $T_{sensing_slot}$ consists of $T_{sensing}$ and RX/TX to tell whether the other candidates detect the ACK.

RTS-CTS Coordination stands for Request-to-Send/Clear-to-Send. It's another approach in control-based coordination which takes advantage of the handshake technique to mitigate the hidden terminal problem. The idea is before sending a data message the sender node will dispatch an RTS message to its neighborhood. The source node is allowed to transmit the data packet only if it receives a CTS from the other nodes within the CS. However, the transmission of CTS has to be done in a specific manner. The candidate with the highest priority can send the CTS after a period equivalent to SIFS, the second one after twice this time ($2 * SIFS$), and so on. Once the source node receives the first

CTS, it starts the data transmission towards the CTS sender after a delay of SFIS. As soon as the data packet has been received successfully, the receiver sends an ACK packet back to the source. Meanwhile, the other nodes switch all their channels on the Network Allocation Vector (NAV).

It is worthwhile noting that this approach solely makes use of the broadcast nature of the wireless medium during the RTS phase. Once the next-hop forwarder is identified by the source, the interaction between them will be conducted in a unicast fashion. Moreover, to implement RTC-CTS technique, some changes are necessary to the standard unicast MAC layer 802.11.

2.6.2 Data-based Candidate Coordination

Unlike control-based candidate coordination, data-based coordination does not rely on any control packets. Simply put, there is no back and forth communication between a source and its CS. The source doesn't have any implication in the forwarding process once it broadcasted the message only nodes in the CS are responsible for all further actions. Common types of data-based coordination include Timer-based or Network Coding (NC), which are explained in more detail in the following sections.

Timer-based candidate coordination is the most straightforward and easy to implement approach for candidate coordination technique. This method resumes the forwarding process up to where the candidate set selection left off. A time slot is assigned to each candidate accordingly to their priority in the CS. After a data packet is broadcasted, the candidate with priority i must forward the packet during its time slot i . Subsequently, Candidate $i + 1$ listens to the channel before its time slot (time slot $i + 1$) arrives. If candidate i failed to forward the data packet candidate $i + 1$ will attempt to forward it at its turn. The same mechanism is applied until the exhaustion of the remaining candidates.

Figure 2.7 illustrates a timer-based coordination scenario where the source SRC has a CS formed by *cand1*; *cand3*. The candidate *cand3* is chosen as the best suited to be the following relay because it has the higher priority. In this example, *cand3* must forward the packet during the first time slot. If *cand1* overhears the data packet sent by *cand3*,

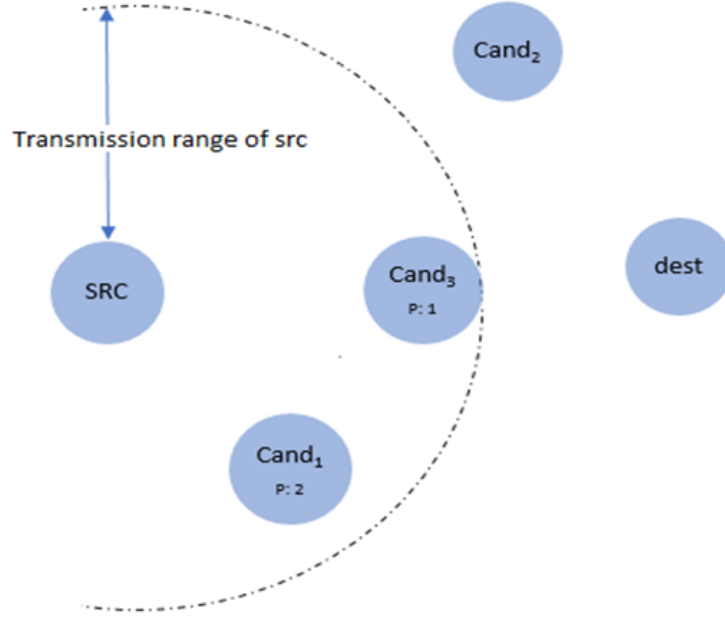


Figure 2.7: Timer-based coordination method

it immediately discards the packet. In case of failure, *cand1* is scheduled to forward the packet in the second time slot.

One of the major drawbacks of this method is duplicate transmissions because there is no guarantee that all the nodes can hear each other and thus the transmission of higher priority nodes. Therefore, nodes with lesser priority will re-transmit the same packet sent by the selected candidate. Another one is the high latency due to the waiting time of the low priority candidates [32].

Network coding candidate coordination (NC) is a coordination mechanism introduced by Ahlswede et al. [28] to mitigate the duplicate packet transmission and packet loss in OR routing. The key concept behind NC coordination is to combine multiple packets in a single packet and broadcast them all in a single transmission [16]. This transmission is done in two forms, namely: native packets (batches of original packets) and coded packets. The data transmitted by a source node is the result of a random linear combination of native packets. The intermediate nodes can then forward the packets towards the destination while repeating the procedure of encoding and broadcasting locally. Whenever the destination gathers a sufficient number of linearly independent coded packets, it can decode

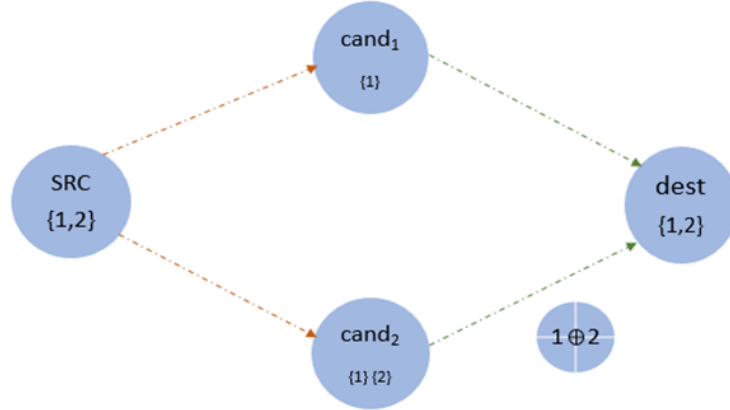


Figure 2.8: Network Coding coordination mechanism

them into native packets. In addition, the network coding technique used in NC can be classified into two groups. The first one is the intra-session NC during which the forwarder only encodes data packet from the same source nodes. And the second technique is the inter-session NC where packets from different source nodes can be encoded simultaneously. If the first technique cited is designed to address the packet loss problem the second one tackles the duplicate packet transmissions issue. The application of NC methods in OR can be seen in Figure 2.8; the source *SRC* is transmitting packet 1,2 to the end-point *dest* through the CS *cand₁*, *cand₂*.

Assuming that *cand₁*, the highest priority candidate, only received part of the packets 1 it will then forward it to the destination node. Then, the other candidate *cand₂* noticing that the message is incomplete will send the missing pieces to the destination. Upon reception of the packets from the relays, *dest* can perform the decoding process and restore the native packets {1, 2}.

This approach presents the advantage of removing the duplicate packet transmission. However, the use of NC in an OR network may generate redundant transmissions. To position it concisely, redundant transmission here refers to packets with no other relevant information. Furthermore, the operation of coding and decoding can be difficult at time and for the computationally limited sensor nodes.

Figure 2.9 Summarizes two of the major components of opportunistic routing protocol: candidate set selection and candidate coordination. In the subsequent section, we will

Opportunistic routing

Candidate set selection

- Candidate prioritization
- Candidate filtering
- Virtual link strength, candidate connectivity, duplicate probability, pruning

Candidate coordination

- Control-based
 - Acknowledgment-Based , RTS-CTS
- Data-based
 - Timer-based, network coding

Figure 2.9: Overview of OR components

discuss the applications of OR in MWNs, by relying on state-of-the-art protocols.

2.7 Opportunistic Routing in Multi-hop Wireless Networks

A multi-hop wireless network refers to a collection of distant nodes connected by wireless communication links. It does not require common infrastructure either centralized control. The predominant medium of transmission of information used in MWN to connect two nodes is the radio frequency (RF). Taking into account the RF communication range very often the distance between two nodes in a multi-hop wireless network can be more than one hop. Scalability is one of the main characteristics of any MWN. For a certain number of nodes deployed within two similar areas, we can have n completely different scenarios (with $n > 2$). One scenario may consist of an area with a high density of nodes and the other one with nodes scattered all over the area. To control nodes distribution and interconnection throughout the network, specific routing protocols are necessary. Hence,

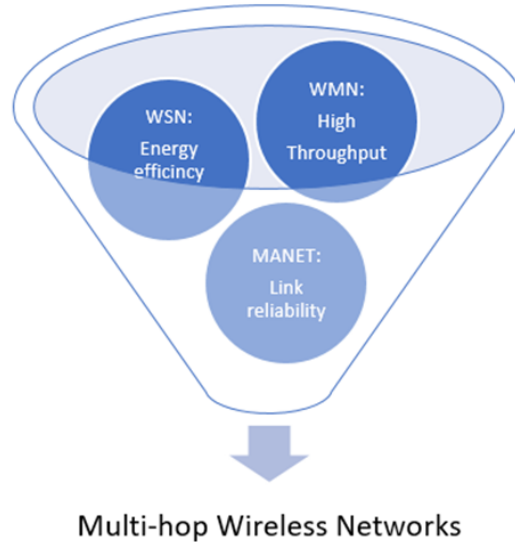


Figure 2.10: Major challenges in MWNs

recent developments in opportunistic routing have been widely investigated to cope with the challenges of multi-hop wireless networks (Figure 2.10). Depending on the capabilities and characteristics of the nodes that form the network, MWN can be divided into three classes, specifically: Wireless Mesh Networks (WMN), Wireless Sensor Networks (WSN) and Mobile Ad hoc NETWORKs (MANET) [53]. The next paragraphs aim to analyze OR in each MWN class.

2.7.1 OR in Wireless Mesh Networks

In [54], the authors define a wireless mesh network as a set of nodes dynamically self-organized and self-configured. Those nodes can be of two types, namely: mesh routers, also called access routers (ARs), and mesh clients [55]. Mesh clients can be either stationary or mobile and can form a client mesh (multi-hop) network among themselves and with mesh routers which have little to no mobility. Because of its reasonable cost and ease of deployment, WMN is considered as an ambitious technical scheme to provide “last kilometer” access [56]. However, the performance of WMNs is affected by many factors like network topology, node density, traffic patterns, transmission power level, node mobility, etc. In previous years, various opportunistic routing protocols have been proposed to

address those challenges. The description of certain of those routing protocols is set out in the upcoming subsections.

Extreme Opportunistic Routing (ExOR)

Biswas et Al in [30] present one of the first opportunistic routing protocol designed for WMNs. To identify the most suitable next-hop ExOR employs the ETX metric. ExOR uses multi-hop mechanism when a node wants to send its collected data towards a distant destination (out of communication range). Hence, between the source node and a specific destination, there are multiple intermediate nodes involved in the data packet transit.

Every time a data packet has to be sent from one point to another, the packet holder must run the ETX metric to determine the best set of next-hop forwarder. As an alternative to ETX, Darehshoorzadeh has suggested the Distance-based MAximum number of Candidate Estimation (D-MACE) as an approach to reduce the number of candidates in each node [57]. Subsequently, among the nodes composing the CS, the closest candidate to the destination broadcasts the packet. If the next node (priority-wise) in the CS fails to hear the ACK message from a higher priority node, it may transmit the packet while the others discard it. In [4], the same authors introduce a new feature to achieve better coordination between the nodes within the CS in ExOR. To accomplish such a goal, they include batch transmission strategy and broadcasts 10-100 packets per batch [42]. In this newest version of ExOR, the forwarders continue to cycle through the CS until the destination received 90% of the packets. The remaining packets are sent using the TR method. Another version

In general, the results suggest that ExOR have higher throughput than TR. However, the main drawback is related to duplicate packet transmission causes by poor link quality between the candidate nodes.

Simple Opportunistic Adaptive Routing Protocol (SOAR)

In [58], the authors proposed SOAR to prevent the forwarding of duplicated messages and to have better transmission control. Similar to the ExOR protocol, SOAR uses the

ETX metric to choose the best set of neighbors to forward the data packet from source to destination. Following that, it filters the resulted CS to select only the nodes located close or along the shortest path so that the nodes can communicate among each other. This technique helps lighten the burden of duplicate transmissions on the network. In addition, a timer mechanism is used to make sure that only the best forwarding node transmits the packet. The timer is set according to the node position in the CS [53]. Also, SOAR incorporates a local loss recovery based on the transmission of cumulative ACK to efficiently detect and retransmit lost packets. Also, according to the network topology, SOAR possesses the capability to determine an appropriate sending rate.

The combination of these techniques enables SOAR to decrease the congestion and load on the network and resolve and effectively support multiple bulk transfer flows. Simulation results have shown that SOAR outperforms ExOR in various scenarios especially when the topology is getting denser.

Opportunistic Any-Path Forwarding (OAPF)

OAPF [59] is a hop-by-hop routing protocol design to exploit the broadcast characteristic of wireless transmission and handle multiple interactive traffic flow. It is based on ETX and EAX metrics to form its candidate set. As reported previously, the EAX metric offers a more proper fit than ETX for OR scheme and enable to calculate the optimal forwarder locally toward the destination.

Comprehensively, to move a packet from a source to a destination, OAPF assembles the CS by adding the candidates individually. First, the neighboring nodes of the source which offers positive progress towards the destination must determine their CS based on the ETX metric. From this point forward, the source will select its set of initial candidates according to the same metric. After initiating the CS, the source selects the candidate that has the lower expected any-path transmission from its location to the destination. Under those circumstances, the selected node will be transferred from the initial candidate set (CS_i) to the final one (CS_f) which already contains the source and the destination information. This process is repeated until there are no other fitting candidates that remain in (CS_i),

or the number of candidates in (CS f) reaches a certain limit. Lastly, the nodes within the final CS are prioritized based on their EAX. Another key factor of OAPF is the candidate coordination which is carried out using the timer-based approach and by the incorporation of a robust acknowledgment (RACK) mechanism, which includes a batch of ACKs in the header of data frames.

Although OAPF offers high delivery ratio and takes care of duplicate packet it has also its disadvantages (latency, moderate computational complexity). For instance, acquiring the updated information of the network topology might be a time-consuming task. Despite those facts, if time factor and computational complexity are not critical to the application, OAPF performs better than ExOR.

MAC-independent Opportunistic Routing and Encoding Protocol (MORE)

In contrast with studies in the OR field, MORE [46] is the first OR protocol to adopt a practical approach based on NC schemes which bypass the need for a coordination mechanism. The ultimate goal of MORE is to decrease the number of transmissions necessary to deliver a packet from one point to another. ETX metric is used to create the CS. Sender node compares its ETX to those of the candidates located within the communication range and selects only the nodes with the lowest ETX to the destination in an orderly fashion.

MORE forwarding system works as follow: Source node transmits a linear combination of native packets in one batch to the relay nodes. It only shifts to the next batch upon reception of ACKs for all the packets of the previous batch. MORE packet header includes the list of the forwarders ID. When a candidate receives a packet, it verifies if the packet contains supplementary or new information. If so, it decreases the counter based on ExNT and transmits the packet. This process is repeated until the packet reaches its intended destination or if the counter reaches zero, a situation where the packet will be ignored.

As reported in several papers, MORE maintains a certain advantage over commonly discussed protocols like ExOR or TR in term of throughput and reliability. Despite that, MORE channels suffer problems related to decoding latency and frequent packet collisions. Moreover, the nodes need to possess sufficient computing capabilities.

A Coding-aware Opportunistic Routing Mechanism for Wireless Mesh Networks (CORE)

In this protocol [7], the authors exploit the combination of OR and localized inter-session network coding concept to maximize the number of packets embedded in each transmission. In CORE, when a node initializes the transmission of an encoded packet, the candidate with the highest coding gain within the CS is chosen to transmit it. This operation is executed continuously until the packet reaches the destination. Each transmitted packet stores the location information of its original sender and forwarder nodes.

CORE CS is formed with the neighboring nodes which are closer to the destination than to the sender in term of DP metric. By the time a node overhears an encoded packet, it decodes it and checks if its ID is in the forwarder list of the retrieved packet. In case its ID is stored as a candidate, it will determine its retransmission timer based on its local coding opportunities and a fixed time interval. When the time of the retransmission timer elapsed, the node will transmit the packet, possibly encoded with other packets. The nodes with less coding opportunities within the CS will stop their timer whenever they hear the successful forwarding of the packet.

The contributions of CORE are substantial when considering the significant improvement in packet delivery and minimization of redundant transmissions compared to other protocols like COPE and OP.

2.7.2 OR in Wireless Sensor Networks

Sensor networks differ from the general wireless networks in performance metrics, traffic patterns, and their amount of available memory and processing resources [60]. The basic idea of a wireless sensor network consists of the deployment of several small and inexpensive wireless sensor nodes over a specific geographic area. They are normally used to monitor various physical or environmental conditions, such as temperature, pressure, and chemical composition [61]. Also, WSNs have great potential for ubiquitous computing applications (e.g. pervasive health monitoring systems, smart homes) [62]. Sensor nodes

have the capabilities to communicate with each other and may form local clusters to relay sensed data to one or multiple collection points (Ex: sink, base station, etc.). Energy efficiency, rapid deployment, and flexibility represent key parameters that make the study of opportunistic routing in WSNs an exceptionally promising approach. In the rest of this section, we describe the main OR protocols in WSNs.

EFFORT

Previous works in OR have been limited to the design of OR protocols that enable high throughput while decreasing end-to-end latency. EFFORT [63], was among the first studies to address the problem of energy consumption for extending the lifetime of a WSN. Naturally, the performance of an opportunistic network depends significantly on the election of a useful metric to set the CS of a given forwarder. Hence, EFFORT routing protocol comprehends a new metric called Opportunistic End-to-end Cost (OEC) which can reflect the diminution of network-lifetime caused by each data transmission.

To initiate the routing process applying EFFORT strategy, the first step consists of the computation of OEC starting from the sink to each node in a recursive fashion. Thereafter, it proceeds with the selection of optimal CS for each sensor node and determines their corresponding relay sequence. Forwarder nodes must transmit an ACK message to the neighboring nodes (including the sender) once it has successfully delivered a packet to the next-hop. As a rule, information like residual energy, link reliability, and updated OEC value, are embedded in the ACK message.

In most cases, EFFORT selection criterion ensures lifetime enhancement and energy-cost reduction for a WSN. However, the network throughput and delay will be affected when a suitable candidate is discarded due to its energy.

Energy-Efficient Opportunistic Routing in Wireless Sensor Networks (EEOR)

The work in [13] exploits the residual energy of each node to minimize energy consumption in the entire WSN. EEOR protocol implies the utilization of Candidate Relay Selection

(CSR) and the cost metrics. The authors discuss two complementary cases to select and order the CSR, namely: The nonadjustable transmission model in which the transmission power of each node is fixed, and the adjustable transmission model in which transmission power can be changed. EEOR also presents four theorems governing the formation of the optimum CS. Based on these theorems, when a source wants to add a particular node to its CS, it considers the impact that operation would have on the CS. If that addition will increase the expected cost; the operation will be canceled.

The authors compared EEOR with ExOR (version adapted to WSNs) with regard to the total energy consumption, packet loss rate, end-to-end delay, and packet duplication ratio. The results support that EEOR performs better than ExOR. However, in [64], Coutinho shows that his proposed protocol, Transmission power Control-based Opportunistic Routing (TCOR), can achieve a reduction of until 80% of the energy consumption per packet in comparison to EEOR.

Energy Saving via Opportunistic Routing (ENS_OR)

[65] has been presented as an energy-efficient algorithm for routing in WSNs. Since sensor nodes are usually static, information such as the distance to the destination and the residual energy becomes crucial to determine the optimal transmission distance. As a result, ENS_OR uses those parameters to ensure minimum energy consumption during the data forwarding phase and preserve the nodes with relatively low residual energy. Moreover, the algorithm implements the concept of Energy Efficient Node (EEN) which happens to be a virtual relay node obtained by relay function on several real nodes based on their residual energy.

The broad idea here is when a source node has a packet to send to a destination, it first computes its optimal transmission distance d_{op} which should be a value between the fixed minimal transmission range d_{min} and the maximum transmission range. Then, it looks for neighboring nodes located close to d_{op} distance of the destination and whose residual energies are higher than itself. Moreover, the eligible nodes prioritize themselves by their distance to the virtual relay node EEN and the energy cost to reach a destination.

EN_SOR was submitted to extensive simulation for 1-D queue network where nodes location is static. The authors claim that their proposed scheme can minimize energy consumption and improve network partition in a WSN.

Opportunistic Network Coding for Wireless Networks (ONC)

An opportunistic network coding, called ONC, is proposed in [66] which develops an optimal strategy to deal with delay and packet loss in WSNs. To carry out this goal, ONC formulates a Markov Chain and a Hidden Markov Model for the delay and power analysis. In conventional NC approaches, if relay nodes have only one packet in its buffer, it has to wait until another one arrives to code them. That wait increases delay and loss rate. In contrast, this paper considers a more practical scenario where packets might be sent with or without coding based on the buffer queue state at a given node. Each timeslot of the buffer queue is divided into two sub-timeslots to allow synchronous reception and transmission of data packets. Hence, a packet can be received in the first sub-timeslot and transmitted in the second one. It is worth noting the buffers can store only a limited number of backlog packets. ONC is comparable to a conventional NC protocol when the probability of forwarding packets without encoding is set to zero.

Through extensive simulation and rigorous mathematical analysis, the authors show there is a delay-power tradeoff when it comes to assessing the network performance. It was also demonstrated that ONC helps diminish the impact of the delay in WSNs compared to conventional wireless networks coding scheme.

Network Coding for Reliable Sensor Networks (SenseCode)

The authors in [60] use network coding to decrease end-to-end packet error rates and energy consumption in WSNs. Taking into account the limited processing capabilities and memory of a sensor network, SenseCode only incorporates simple and decentralized algorithms. In the design of the protocol, it is assumed that the sensing task is performed by sensor nodes on a periodic basis. It is based on a modified tree structure where each node has to send their sensed data and up to 10% of the packet it overhears to a common collecting point

during a round. The authors justified their strategy using a traditional tree-based scenario as an example. They prove that in case of node or link failures of a forwarding node (a parent) the data will not be delivered to the final destination.

In the SenseCode framework when a node has to transmit a message to a destination, it initially creates an "uncodable" packet that contains the message called the original packet. In addition, it generates $R - 1$ linear combinations of the uncodable packet, and marks them as "codable." Note that R is defined in the paper as a configurable redundancy factor. The destination requires a sufficient number of linearly independent combinations of the packets to transform the data received into meaningful information. This number should be equivalent to the number of new messages gathered during the transmission process. However, SenseCode guarantees a significant number of packets will be delivered to the sink node and thus a certain reliability.

The results show that SenseCode can achieve over 90% link reliability in high dynamic network condition whereas the performance of the well-known collection tree protocol (CTS) will drop by 75%.

2.7.3 OR in Mobile Ad Hoc Networks

Another type of wireless sensor networks is the mobile ad hoc network which is a continuously self-configuring, infrastructure-less network of mobile devices connected by wireless links [67, 29, 33]. A MANET is usually modeled as a *unit disk graph* where two nodes are connected if and only if their geographical distance is smaller than a given transmission range [68]. The principal challenges in MANETS are the intermittent network connectivity (with new nodes joining and/or existing nodes departing), the variable link performance, and the maintenance of routing information at each node [69]. In an attempt to tackle those challenges several researchers have suggested the use of OR techniques to regulate forwarding decisions, data dissemination, and resource usage. More details about some of these studies follow below.

Geographic Random Forwarding (GeRaF)

GeRaF [27] is a transmission scheme designed for MANET leveraging the opportunistic features of the communication medium. The goal is to minimize the amount of time the nodes are in an active mode to drastically reduce energy consumption while guaranteeing connectivity and bandwidth throughout the network. In this view, GeRaF incorporates an effective strategy where nodes alternate between active and inactive mode according to a specified duty-cycle. GeRaF forwarding technique relies on the assumption that all the nodes can determine their own position as well as the position of the intended destination. Once a node has a packet to transmit it chooses the active neighboring node located the closest to the destination among its eligible candidates. The same procedure is repeated in a hop-by-hop manner until the packet reaches its final destination. The coordination method employed in this protocol is RTS-CTS which helps to prevent packet collision.

The major benefit of GeRaF resides in the fact that it is simple to implement and use. However, in a scenario where the network density or the duty-cycles is low, the probability of finding the best relay to advance the packet toward its final destination might be significantly affected [70].

Opportunistic Routing in Dynamic Ad Hoc Networks (OPRAH)

In the late 2010s, the application of OR in a mobile ad hoc network environment has been neglected compared to WMNs and WSNs. To solve this shortage, OPRAH was proposed in [71]. In this paper, the protocol is designed to leverage the distance between a source and a destination to discover an optimal path for each packet while considering the characteristic of a dynamic network. It uses the number of hops to the destination as the metric for generating the CS. A path is deemed optimal when its number of hops is inferior to those of another one which allows reaching a common destination. OPRAH protocol is divided into two phases: the first is the route-setup. During this phase, the nodes fill their routing tables by sending on-demand route requests and gathering the information received when the other nodes reply. The second phase is the forwarding phase, where a

source node will use the list of candidates of its CS to chose the best path that leads to the destination.

The principal advantage of OPRAH is it can ensure a certain level of link reliability. In addition, it is not difficult to implement and does not require any modification of the MAC layer. However, the results presented in [71] could have been more realistic if the link and the channel quality were considered in the CS process. Lastly, OPRAH is prone to high packet loss rate because of the absence of a mechanism to control duplicate data transmissions.

History Based Opportunistic Routing Protocol (HiBOp)

In [5] the authors investigated a distinctive approach for OR in MANETS than the previously discussed routing protocols. The approach emulates the establishment of social relationships among people to shape a social-aware forwarding algorithm for opportunistic routing. This context-based protocol, HiBOp, aims to mitigate resource consumption and latency of MANETS. HiBOp scheme comprises three different contexts which are: the context of the node, the context of its neighborhood, and the historical context. The management of these contexts helps to determine the goodness of the wireless link of eventual forwarder nodes and their similarities with the destination node. In this respect, HiBOp draws social relationships between nodes and their neighbors and implicitly learns the network social structure defined by the nodes history.

In HiBOp when a sender wants to transmit a packet to a destination, it generates several copies of the packet during a timeslot that follows an exponential distribution. Once a packet is delivered to a next-hop, the sender discards it automatically. HiBOp runs an algorithm (the target delivery probability) to control packet spreading allowing the reduction of the packet loss. It is important to note that this protocol is not restrained to any predefined set of information. The simulation results show that HiBOp in comparison with other popular solutions has lower buffer occupancy and networking overheads. However, it introduces higher delays and might require additional time to learn the context information.

Cooperative Opportunistic Routing in Mobile Ad Hoc Networks (CORMAN)

Wang et al. proposed in [72] a network layer scheme compatible with any off-the-shelf wireless networking equipment to address the nodes link quality fluctuation over time. The cooperative communication algorithm introduced in the study is called CORMAN. Its node coordination mechanism is inspired primarily by ExOR with the necessary complement of nodes mobility features. CORMAN uses a proactive source routing (PSR) approach so that each node maintains an updated interactive map of the network topology. Moreover, it can handle multiple concurrent data flows. Several nodes are included in the operation of moving a packet from a source to an intended destination. However, only the candidates that can help the packet to reach the destination are selected to compose an associated forwarder list. When forwarding data packets, the intermediate nodes must update the forwarder list using the information of its current neighbors to have a real-time map of the network. This introduces the backoff time of the DATA frame in order to reflect the traffic load in the network [72].

To tackle the link variation, CORMAN uses a small-scale retransmission technique to increase the reliability of data forwarding. Simply put, if a forwarder node failed to receive a packet after a few attempts, the protocol would use the channel diversity approach. Therefore, a node that does not figure in the current CS but is located along the established path is allowed to transmit the packet.

To conclude, the authors claim that CORMAN through cooperative communication promotes minimal overhead and therefore displays a strong resilience to link quality fluctuation and node mobility. It also demonstrates superior performance measured in throughput, latency and delay jitter.

Network Coding-Based Broadcast in Mobile Ad-hoc Networks (CODEB)

A coding based broadcast protocol which exploits the coding opportunities to reduce the number of packet transmissions for MANETs is introduced in [73]. CODEB combines three essential techniques, namely: opportunistic listening, forwarder selection, and pruning, and

opportunistic coding. CODEB performs opportunistic listening to drive each node to snoop all packets that it overhears and stores them for a limited period, T . Moreover, each node periodically broadcast all the nodes it can hear to its one-hop neighbors so that they acquire the updated information of their two-hop neighbors. This step is used to build CODEB broadcasting backbone [74]. This technique helps to reduce the number of packet transmissions as it prevents a forwarding node from transmitting if it determines that all its neighbors have received the given packet. Afterward, the authors implemented the Partial Dominant Pruning (PDP) algorithm [75] which represents a local forwarding method, to select a subset of next-hop candidates deterministically during the forwarder selection and pruning phase. It is pointed out that in CODEB approach, the CS of each node contains minimum information about the packets received from its two-hop neighbors.

The proposed scheme relies on opportunistic coding technique to determine the scenario when a node is allowed to forward coded packets to its neighbors. The opportunistic coding is composed of two coding algorithms, specifically: X-OR based algorithm and Reed-Solomon-based algorithm. The former enables the nodes to decode the packets without delay handling only the packets in their buffer. Unlike X-OR based algorithm, the Reed-Solomon algorithm requires a node to wait until it receives a sufficient number of coded packets to initiate the decoding process.

It has been shown that CODEB can be an attractive alternative for application in MANETs. It significantly enhances the packet delivery ratio and the number of transmissions required to deliver a packet to all nodes in the network. However, CODEB may introduce coordination overhead and packet loss when dealing with rapid topology changes

2.7.4 Summary

This chapter surveyed the challenges and the benefits of opportunistic routing in multi-hop wireless networks. We proceeded by defining the concept of routing protocols and subsequently discussed the dominant approaches to exchange information within the wireless network. Afterward, we described the characteristics and the different elements of opportunistic routing in wireless an environment. In addition, we elaborated the basic concept

of several of the most cited protocols designed for MWNs. The previously mentioned protocols are summarized in Table 2.3.

Table 2.3: Classification of Opportunistic Routing protocols in MWNs

<i>Protocol</i>	<i>Metric</i>	<i>Candidate Set Selection</i>	<i>Candidate Coordination</i>	<i>Objective</i>	<i>MWN Model</i>
<i>CODEB [73]</i>	PDP	End-to-end	Data-based	Throughput	MANET
<i>CORE [7]</i>	DP	Hop-by-hop	Data-based	Throughput	WMN
<i>CORMAN [72]</i>	Hop-cnt/ETX	End-to-end	Control-based	Throughput	MANET
<i>EEFORT [63]</i>	OEC	End-to-end	Control-based	Energy efficiency	WSN
<i>EEOR [13]</i>	Cost	Hop-by-hop	Control-based	Energy efficiency	WSN
<i>ENSOR [65]</i>	Hop_cnt	End-to-end	Control-based	Energy efficiency	WSN
<i>ExOR [4]</i>	ETX	End-to-end	Control-based	Throughput	WMN
<i>GeRaF [27]</i>	DP	Hop-by-hop	Control-based	Link quality/ Energy eff.	MANET
<i>HiBOP[5]</i>	Context	End-to-end	Control-based	Throughput	MANET
<i>MORE[46]</i>	ETX/EOTX	End-to-end	Data-based	Throughput	WMN
<i>OAPF [59]</i>	ETX/EAX	End-to-end	Control-based	Throughput	WMN
<i>ONC [66]</i>	NA	End-to-end	Data-based	Throughput	WSN
<i>OPRAH [71]</i>	Hop-cnt	End-to-end	NA	Throughput	MANET
<i>SenseCode [60]</i>	E2E/TX	End-to-end	Data-based	Throughput/ Energy eff.	WSN
<i>SOAR [58]</i>	ETX	End-to-end	Data-based	Throughput	WMN

Chapter 3

Opportunistic Routing for UWSNs

This chapter is organized as follows. Sections 3.1 to 3.2 provides an overview of the basics of acoustic communications, deployment and network architecture, localization and reliability related issues. The introduction of the principle governing the numerous techniques used to approach wireless communication in a mobile ad hoc underwater network draw on prominent examples is done in section 3.3. In Sections 3.4 and 3.5 provides a brief review of geographic routing protocols and sheds some light particularly on the pressure-based routing protocols. DBR, EEDBR, Hydrocast, GEDAR, and VAPR protocols are dealt with in more detail in Sections 3.6 to 3.10. Finally, Section 3.11 presents the final remarks.

3.1 Introduction

The oceans cover more than 70% of the planet; they hold about 96.5% of all of Earth's water and are bursting with wildlife and teeming with mysteries to be solved [76]. In 2007, it has been reported that about 5% of the ocean floor has been carefully mapped, which means we know less about 65% of the Earth's landscape than about the far side of the Moon [1]. In addition, due to the harsh ocean conditions (high pressure, impenetrable darkness at depth) it is virtually impossible for humans to conduct oceanographic research on their own in deep water. Therefore, considering the wide applications of wireless sensor networks, researchers are trying to discover new ways to use acoustics to reveal vital facts

about the interior ocean and the behavior of undersea life. Since radiofrequency (RF) waves are seriously attenuated in the underwater environment [9], underwater sensor nodes use acoustic waves rather than RF wave to communicate with each other. Throughout this paper, the terms "underwater wireless sensor network" and "underwater acoustic sensor network" are used interchangeably.

Considering the differences between the terrestrial and the underwater environment, a lot of efforts are put in the UWSNs area in order to seek better ways to observe the ocean. One of the most common problems encountered is to determine an efficient and reliable routing between the source node and the destination node. Therefore, designing efficient and robust routing protocols that consider the intrinsic characteristics of underwater communication become an attractive topic for researchers. The current trend in UWSNs is to combine weak links and create a stronger virtual link by taking advantage of OR scheme [77].

This chapter seeks to address in detail the key factors of an underwater sensor network. It also calls into question 5 state-of-the-art routing protocols proposed for UWSN: The Depth-Based Routing protocol (DBR) [12], the Energy-Efficient Depth-Based Routing protocol (EEDBR) [8], the Hydraulic-pressure-based unicast routing protocol (Hydrocast) [14], the Geographic and opportunistic routing protocol with Depth Adjustment for mobile underwater sensor networks (GEDAR) [10], and the Void-Aware Pressure Routing for Underwater Sensor Networks (VAPR) [15]. The study of these protocols pinpoints the advantages and limitations of each approach.

3.2 Background

In this section, we will introduce the related principles of routing protocol design, the underwater wireless sensor network applications, and the key challenges in underwater communications that influence routing protocol development.

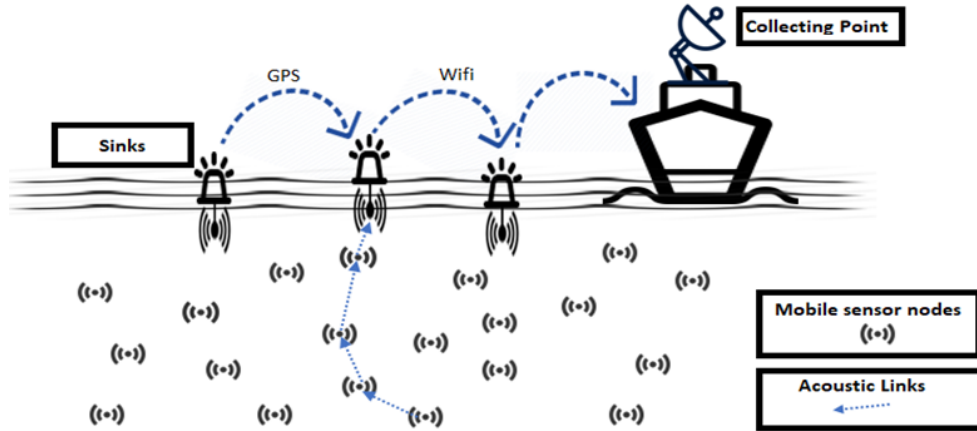


Figure 3.1: Common architecture of UWSNs

3.2.1 Underwater Wireless Sensor Networks: general scenario

Underwater sensor networks consist of a variable number of sensor nodes that are deployed over a certain region of the sea to perform collaborative monitoring. There are two types of sensor nodes in a UWSN which are the sink nodes (sonobuoys) and the ordinary/diving nodes. The former is deployed on the ocean's surface and uses radio waves to communicate between the sinks and a monitoring center. Concerning the ordinary nodes, they are deployed underwater with usually acoustic links as a communication medium. Ultimately, every ordinary node should be able to establish multi-hop paths in order to reach the surface sink. Figure 3.1, illustrates the underwater wireless sensor network architecture.

3.2.2 Underwater Wireless Sensor Networks applications

The UWSNs has many attractive applications especially for short-term ad hoc real-time aquatic exploration such as oil/chemical spill monitoring, water temperature and salinity, anti-submarine missions, and surveillance. It is well-known, that the nodes are deployed under the ocean for a short period due to battery limitations and cost of deployment. The wireless communication in the underwater medium is set to become a vital factor in the conquest of the ocean because it reduces deployment costs compared to the wired network; it is scalable, and it can be accessed remotely.

3.2.3 Underwater Wireless Sensor Networks Challenges

Various studies on the potential of UWSNs have been carried out in the last decades, however, there are still some critical issues regarding the design and deployment of a robust UWSNs. Since an underwater sensor network is used to collect data when events occur in the submarine environment, a reliable and effective route from a source node to the destination node using acoustic multi-hopping is necessary. As shown in Table 3.1, the aforementioned process is challenging because compared to terrestrial radio communications, acoustic communications are very energy hungry and have very low bandwidth, and long propagation delay, and nodes are mobile due to water current. For a better understanding of the challenges face in routing protocol design for UWSN, an investigation of its characteristics is introduced in the following paragraphs.

High Propagation Delay and Low Bandwidth

In the submarine environment acoustic communication is preferred over radio frequency and optical alternatives due to greater reliability and range. It is well known that acoustic waves are caused by oscillations of pressure within an area. Since water has a greater density than air, they travel 4-5 times faster than they do in the air. It should be noted that the propagation speed of an acoustic channel is affected by the variations of depth, temperature, suspended particles of the water body, salinity and sound speed. These delays will have a great effect on the routing protocol performance; it can even disable the routing if not consider properly. Moreover, considering that acoustic waves have high power absorption in the underwater environment, only a few frequencies can be used to communicate over a long distance. Consequently, this represents a great limitation in UWSN routing protocol design based on acoustic communication, especially considering that the routing protocols need large amounts of information exchange during routing discovery and routing maintenance [11].

Dynamic Networks

Undersea level the sensor nodes can move passively with water currents, therefore, the topology changes frequently, which results in improper communication. These dynamic networks introduce significant background operation that doesn't directly involve sending and receiving messages (communication overhead). Moreover, the bandwidth of a submerged can also be affected by the transmission power, radio frequency and transmission distance [78]. As a result, a dynamic network would provoke temporary lost of connectivity, and poor connection between neighboring nodes. Therefore, when designing a routing protocol, different motion models must be taken into consideration. In summary, the aforementioned characteristics severely degrade the link reliability.

Energy Efficiency

Sparse deployment of sensors in marine network and frequent data packet retransmission leads to vast amounts of energy consumption. Also, the energy storage device, usually a battery, of the sensor nodes is hard to replace or recharge when submerged. Therefore, energy efficiency is an important concern to consider when designing a routing protocol for UWSNs.

Spreading Loss

The propagation of an acoustic wave from a sound source spreads the transmitted energy in an omnidirectional fashion (spherically) over a surface. Since all the energy is not directed in a single direction, a significant quantity of that energy is lost. This process is known as spreading loss. This transmission loss is a crucial parameter for acoustic systems, as it constrains the amplitude of the signal received, hence the receiver performance, directly dependent on the signal-to-noise ratio.

High Noise and Interference

Lastly, high noise and interference can affect the performance of an underwater sensor network. In general, they are caused by ambient noise and man-made noise. The former is mainly engendered by machinery noise and shipping activities, while the latter is due to the water currents, rain, wind, and to seismic and biological phenomena.

3.2.4 Underwater Acoustics Channel

Underwater acoustic channels are widely considered to be the most difficult communication media as a result of extremely limited bandwidth. When acoustic waves propagate, they are subject to different constraints such as loss of intensity because of geometric spreading, absorption of acoustic energy by the propagation medium itself, and noise. Within the framework of these criteria, the underwater acoustic networks are designed to elude those constraints by relying on a multi-hopping routing strategy rather than an end-to-end communication to transmit a data packet. The correlation between the acoustics propagation and the distance and frequency variables is evaluated in the following subsections.

3.2.5 Underwater Acoustic Propagation

Attenuation or path loss is the combination of geometric spreading and absorption. Spreading happens when the sound moves outward from a source in expanding spherical wave fashion. Absorption is the conversion of acoustic energy to other forms of energy (i.e. heat in this case). The attenuation suffers by an acoustic channel can be expressed as:

$$A(d, f) = d^k * a(f)^d \quad (3.1)$$

Where d represents the distance covered, and f the signal frequency. The variable k is the spreading factor which is used to describe the geometry of the signal propagation. It can vary from 1 (cylindrical spreading) to 2 (spherical spreading). In the literature, researchers tend to use a spreading factor of 1.5 in order to recreate a more practical

Table 3.1: Comparison between terrestrial and underwater wireless sensor networks [1]

<i>Terrestrial WSNs</i>	<i>Underwater WSNs</i>
Most applications require dense deployment	Sparse deployment is preferred not only due to expensive equipment but also in order to cover large monitored areas
Most of the network architectures assume that sensor nodes are stationary so different topologies can be applied	Nodes continue to move 1-3 m/s with water currents, so the network cannot be viewed as a fixed topology
Nodes are considered moving in 2D space even when they are deployed as ad hoc and as mobile sensor networks	Nodes can move in a 3D volume without following any mobility pattern
Usually, the destination is fixed and seldom changes its location. In the event when destination changes its location, still these movements are predefined	Sinks or destinations are placed on the water surface and can move with the water current. Due to random water movement, predefined paths are difficult to or cannot be followed
Radio waves are available; nodes can communicate with low propagation delays at speed of light (3×10^8 m/s)	Acoustic waves replace radio waves (at speed of 1.5×10^3 m/s). Communication speed is decreased from speed of light to speed of sound, results in high propagation delays (five orders of magnitude). It can be problematic for real-time applications
High data rate, normally in the order of MHz	Low data rate, normally in the order of KHz. Hardly can exceed 40 kb/s at 1 km distance. Moreover, the attenuation of the acoustic signal increases with frequency and range
Low energy consumption	High energy consumption due to longer distances (a consequence of sparse nodes deployment) and complex signal processing. The power required to transmit may decay with powers greater than two of the distance
Larger batteries can be used and can be replaced or recharged with ease	Battery power is limited and usually cannot be easily replaced or recharged. The routing protocols should adopt a mechanism of power down during the communication and use minimum retransmission
Nodes are less error-prone and can continue to work for a longer time	Nodes are more error-prone and can die (due to fouling or corrosion) or leave the working area. More reliable and self-recovering routing algorithms are required

scenario. The last variable $a(f)$ constitutes the absorption coefficient. Its expression in dB/km using the Thorp's formula with a frequency in kHz is given by:

$$10\log(a(f)) = 0.11 * \frac{f^2}{1 + f^2} + 44 * \frac{f^2}{4100 + f} + 2.75 * 10^{-4} * f^2 + 0.003 \quad (3.2)$$

3.2.6 Noise

As stated in Subsection 3.2.3, the underwater acoustic network is prone to be affected by ambient noise. According to Stojanovic [79], this noise is often approximated by Gaussian statistics and a continuous power spectral density. Equation 3.3 illustrates the contribution of the major noise sources in the underwater environment, $N(f)$ in [dB re μPa]/Hz, used to describe the power spectral density for a given frequency f in kHz.

$$\begin{aligned} 10\log * N_t(f) &= 17 - 30 * \log(f), \\ 10\log * N_s(f) &= 40 + 20(s - 0.5) + 26\log(f) - 60\log(f + 0.03), \\ 10\log * N_w(f) &= 50 + 7.5w^{\frac{1}{2}} + 20\log(f) - 40\log(f + 0.04), \\ 10\log * N_{th}(f) &= -15 - 20\log(f) \end{aligned} \quad (3.3)$$

Where N_t represents turbulence noise, N_s refers to shipping noise, s is the shipping activity whose value fluctuates between 0 and 1 (light to dense), N_w denotes the waves noise, w depicts the wind speeds in m/s, and N_{th} the thermal noise.

3.2.7 Packet Delivery Probability Estimation

First, the Signal-to-Noise Ratio (SNR) over a distance d is presented as:

$$\Gamma(d) = \frac{E_b/A(d, f)}{N_o} = \frac{E_b}{N_o * d^k * a(f)^d} \quad (3.4)$$

where E_b and N_o are constants that represent the average transmission energy per bit and noise power density in a non-fading Additive-White-Gaussian-noise (AWGN) channel. To help characterize the fading effects in a mobile digital communication system, the small scale fading also called Rayleigh fading is used. The modulation technique selected to

modulate the carrier wave is the Binary Phase Shift Keying (BPSK). After going through those procedures, the delivery probability of a packet of m bits from a source i to a destination j is calculated as:

$$p(d_{i \rightarrow j}, m) = (1 - p_e(d_{i \rightarrow j}))^m \quad (3.5)$$

Where p_e is the probability of error.

3.3 Related Work

In the last few years, several studies have been carried out on the design and strategies to overcome the challenges in the underwater wireless sensor network. These studies have tended to focus on different approaches to enhance the end-to-end communication among sensor nodes, such as the cross-layer protocol, the topology control protocol, and the geographic routing protocol. As follows, we will introduce the principle of each concept and describe briefly the major works associated.

3.3.1 Cross-layer Protocols

Although, most of the existing studies in wireless sensor network are based on classical layered protocols approaches, in recent years, the cross-layer designs have become increasingly popular. Because of the different application requirements, there is a need to provide differentiated-service support to delay-sensitive and delay-tolerant data traffic as well as to loss-sensitive and loss-tolerant traffic [80, 81]. In other words, the goal of a cross-layer protocol is to create a robust network by increasing information sharing between different layers and deliver multimedia content with a certain level of Quality of Service (QoS).

Multimedia Cross-layer Protocol

In [80], the authors proposed a modular design approach based on three communication methods: a 3D geographical routing algorithm (routing functionality), a novel hybrid dis-

tributed CDMA/ALOHA-based scheme to access the bandwidth-limited high-delay shared acoustic medium (MAC functionality), and an optimized solution for the joint selection of modulation, Forward Error Correction (FEC), and transmit power (physical functionalities). The combination of these key functionalities integrated into a cross-layer module allows the efficient utilization of the bandwidth-limited high-delay underwater acoustic channel.

Novel Cross-Layer Routing Protocol (NCRP)

NCRP, is a cross-layer routing protocol based on network coding for underwater sensor networks. The process of NCRP can be divided into two parts: initial routing construction and route maintenance [82]. In this protocol, the next-hop selection mechanism is built in such a way that the candidates are selected based on the reliability of the data transmission link. As a result, considerable progress has been made in term of channel utilization, packet delivery ratio, and void areas avoidance. It should be noted that *void area* occurs when a packet cannot be delivered to the next hop, when the current node is the closest one to the destination [83].

3.3.2 Topology Control Protocols

A key problem with much of the literature regarding UWSN is node mobility. The unique characteristic of the underwater environment makes it difficult to adopt the same technique used in a terrestrial wireless sensor to control a given topology. To solve this particular issue, many studies have been published under the theme “topology control protocol”. A topology control protocols purpose is to stabilize and smooth the undesirable changes in the network caused by the variable link quality, involuntary mobility, and node failures, which avoid frequent data exchange for the localization of nodes, neighborhood discovery, and data route recalculation [78].

Mobility-aware Distributed Topology Control for Mobile Multi-hop Wireless Networks

A mobility-aware distributed topology control approach based on mobility prediction to reduce transmission power and maintain connectivity is introduced in [84]. In this protocol, each source runs a distributed algorithm to estimate the minimum power required to choose the most desirable neighboring nodes for the transmission of a packet. In addition, each node must send a HELLO packet with certain information to its immediate neighbors. According to the author, the application of their protocol in a dynamic ad hoc wireless environment will help to improve the power consumption and low bandwidth problem. However, Linfeng et al [6] found that the performance of the algorithm was dependent on the accuracy of prediction and mobility pattern, resulting in the difficulty of predicting locations after node movement in underwater environments.

Power Adjustment Distributed Topology Control (PADTC)

Authors in [85], proposed a new strategy to reduce the impact of the local maximum problem by implementing a topology control mechanism made up of the adjustment of the communication range and the depth. It is important to note that in a submarine environment moving a node from one location to another is the most expensive operation energy-wise. Each node displacement per meter costs 15 J of energy [85]. Therefore, in PADTC an isolated node only performed the depth adjustment procedure if and only if it fails to find a neighbor after increasing its transmission range. This technique improves network connectivity and minimizes energy consumption while preserving the throughput.

3.3.3 Geographic Routing Protocols

A Geographic routing protocol, also called position-based routing, is among the most widely investigated aspects of an underwater wireless sensor network. In the field of UWSN, the term usually refers to data packets transmissions in mobile sensor networks from a source (a submerged node) to a final destination on the water surface (a sink) on a hop-to-hop

basis. The aforementioned protocol is very promising particularly in hostile environments because it does not add any burden in the network design although the localization process itself in this kind of routing is an intrinsic source of communication errors [86]. The aim of this paper is restricted to this latter aspect of the underwater wireless sensor network.

3.4 Geographic Routing Protocol Network Architecture

In geographic routing protocols, each sensor node must be able to determine its own location on a three-dimensional reference system for message relay. It can be classified into two categories: unidimensional, and multidimensional.

3.4.1 Multidimensional Geographic Routing Protocol: Location-based Routing Protocols principles

In a multidimensional geographic routing protocol, new variables are involved in the network architecture in order to acquire two-dimensional or three-dimensional location information of each targeted components. Those new variables are constituted of sensors equipped with multiple acoustic transceivers, sensor nodes that are anchored to the bottom of the ocean, and/or autonomous vehicles. In these scenarios, data transmission can be sent towards the water surface receiver via direct links or through a multi-hop path. It is also worth noting that the above-mentioned approach presents encouraging results, [31, 87], for detection and observation of submarine phenomena that cannot be adequately monitored by traditional means.

3.4.2 Unidimensional Geographic Routing Protocol: Pressure Based Routing Protocols Principles

The pressure-based routing protocols utilize the depth information as its main parameter. As a result of the variations of the water pressure at different depths, pressure sensors can be used to determine the vertical position of each node locally. Neighboring nodes with less deepness i.e. nodes that are located in the positive progress area toward the sink when compared to the sender node participate in the forwarding process. Thus, the pressure-based routing protocols rely on a greedy forwarding technique in order to bring the data packet from a sender node closer to the neighbor that is most suitable from a local point of view. There are many strategies used to reduce the number of candidate nodes such as residual energy, holding times and threshold nodes. The key point in data routing is to enable the data packets to reach the sink node using the minimum number of nodes while keeping energy balanced and preventing the communication void problem. This kind of protocol is both scalable and flexible with changes in topology without the use of routing discovery and maintenance which makes it well suitable for large-scale sensor networks with limited resources [88, 89].

3.5 Classification of Pressure-based Routing Protocols

A vast majority of pressure-based routing protocols has used the broadcasting nature of acoustic sensor networks to select the node closest to the destination to be the next forwarder (opportunistic routing technique). Over the last two decades, several authors have classified the unidimensional geographic routing protocols based on various approaches. The most common criteria are the localization, the mobility, the time delay, and the energy efficiency. In this paper, the differentiating factor is the routing technique and the resulted classes are the flooding-based and the cluster-based packet-forwarding strategies.

3.5.1 Flooding-based Packet Forwarding Strategy

The principle of a flooding-based routing protocol is to transmit a packet in a one-hop fashion i.e. to all the nodes located in the transmission range of a source node. The goal is to define the positive progress area towards a sonobuoy i.e. identify the region located between the forwarder node and the closest surface sonobuoy. To ensure the packet delivery from a source to a destination this kind of routing broadcast periodically small packets (beacons) to advertise their position and allow other nodes to maintain a one-hop neighbor table [90]. Although this approach does not require the network topology characteristic, it suffers from energy loss due to the transmission of duplicate packets and void area problem. A detailed description of two flooding-based protocol is given in sections 3.6 and 3.7.

3.5.2 Cluster-based Packet Forwarding Strategy

As for the cluster-based routing protocols, clusters are formed between nodes which are one-hop away from a cluster head. In the literature, Cluster head and cluster member usually refer respectively to the source node its neighbors. All cluster members transmit their node IDs, location information, its node values, etc. to the cluster head. To find the shortest path and to improve the network robustness against failure of individual nodes the local forwarding process involves all the cluster members instead of just one single candidate based on the transmission schedule criteria used. A thorough analysis of three cluster-based protocols will be given in sections 3.8, 3.9, and 3.10.

3.6 Depth-Based Routing Protocol (DBR)

In this section, we present the DBR protocol in detail.

3.6.1 Protocol Overview

DBR is recognized as being one of the most important pressure-based routing protocols in the late 2000s. Its network architecture is composed of multiple stationary sinks deployed on the water's surface and ordinary nodes randomly scattered to different depths under the sea level with water current governing their movement. It uses the greedy algorithm strategy to route a packet from a submerged source to a receiver located on the water surface. Void region permitting, during each step of the DBR routing process, the data packet is transmitted from nodes in deep water to nodes with shallower depth until it reaches the sinks. Consequently, in this protocol, it is fundamental that each node is equipped with a pressure sensor to determine its own depth.

In [12], before initiating the transmission process each node adds its depth and ID information in the data packet to send. Once done, the node starts to transmit the packet to all other nodes within communication range (broadcast). After the transmission is completed, the neighboring node then compares its current depth to the embedded depth in the packet. If its depth is lower than the one inserted in the data packet it can mark itself as a next-hop forwarder otherwise the packet will be dropped. Usually, more than one neighbors are selected and when it is their turn to broadcast the packet it will give rise to duplicate transmission, high collision risk, and high energy consumption within the network. The next section examines the alternatives proposed by the authors to tackle those problems.

3.6.2 Protocol Design

Prior to the description of the redundant packet suppression technique employed in the DBR protocol, it is noteworthy mentioning the packet format structure used. As shown in Table 3.2 DBR's data packet is divided into four segments. The first three segments are considered as the packet header. It contains information such as the source node identifier (Sender ID), the packet sequence number, and the sender depth. The remaining segment is where the data is stored.

Table 3.2: DBR packet format

<i>Packet Header</i>			<i>Storage</i>
Sender ID	Packet Sequence number	Depth	Data

In the suggested scheme, each node maintains two queues. First is the priority queue (Q1) characterized by the scheduled sending time, and the second is the packet history buffer (Q2) which is composed of the Sender ID and Packet Sequence Number. Q1 helps control the number of forwarding paths thus reduce the collision risks. Q2 intervenes in the control of duplicate packet transmission.

When a source node is sending a packet, first it checks if the second queue is properly populated i.e. if the transmitted packet information is recorded into Q2, and then it removes the packet from its priority queue once the transmission is done. When it comes to the packet reception, first, the receiving nodes insert the packets in its priority queue and holds it during a certain time based on the depth difference between the sender and its own (holding time). Second, it computes a sending time based on the holding time and the reception time. The equation of the holding time is presented in Equation 3.6. Evidently, the shorter the holding time the higher the packet priority.

$$f(d) = \frac{2\tau}{\delta} * (R - d), \delta \in (0, R] \quad (3.6)$$

Where $\tau = \frac{R}{V_0}$ is the maximal propagation delay for one hop, V_0 is the sound propagation speed in water, R is the maximum transmission range, d is the depth difference between the receiving and the source nodes, and finally, τ a global parameter to replace $(d1 - d2)$.

At last, the authors also introduce another variable called depth threshold d_{th} , which role is to control the number of nodes involved in the forwarding process the energy and thus control the energy consumption. The main idea is to compare the depth difference between the sender and receiver nodes to d_{th} . The receiver will set itself as a next forwarder only if the result is greater than the depth threshold. Choosing a large d_{th} implies a smaller number of hops to reach a sonobuoy.

Figure 3.2, illustrates an immersive scenario of the different interactions that are hap-

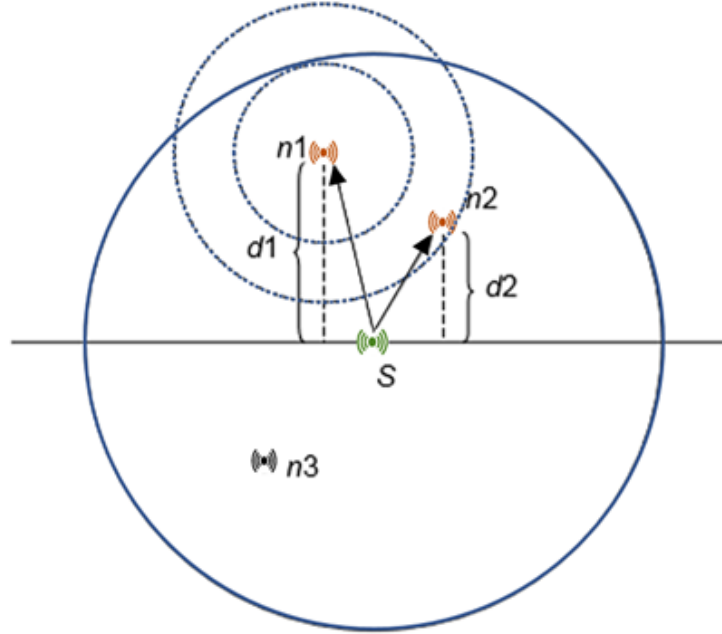


Figure 3.2: Forwarding node selection

pening locally within the network. The green node is the source node S , the solid circle is its communication range. The source node has three neighbors $n1$, $n2$, and $n3$. During the initial step, node $n3$ is disqualified as a next hop forwarder because it is localized deeper underwater than its counterpart node S . Moreover, the application of the DBR redundant packet suppression technique indicates that node $n1$ has the priority over node $n2$. Hence, node $n2$ will only transmit if it does not receive the same packet from the prioritized node and its scheduled sending time for that packet is expired.

3.7 An Energy Efficient Localization-free Routing Protocol for Underwater Wireless Sensor Networks (EEDBR)

The Energy-Efficient Depth-Based Routing protocol is analyzed in the next subsections.

3.7.1 Protocol Overview

The main challenge encountered when deploying an underwater acoustic sensor node is the limited battery resources of the submarine nodes. The harsh environment that characterizes the aquatic ecosystem makes it difficult and very costly to recharge or replace sensor batteries once deployed. Similarly, to DBR protocol, EEDBR is a localization free routing for greedy pressure-based routing protocol where the data packets are transmitted to the sonobuoys in a hop-to-hop manner. The network architecture is composed of two groups of components. The first group is constituted by the nodes deployed from the deep-sea floor to the water surface using acoustic links to form the underwater part of the network. And the second is formed by acoustic and radio capable sinks that float on the water surface. The aim of the protocol in [8], is to propose a constructive framework for improving the network lifetime and balancing node energy. The depth along with the residual energy are the two main parameters used to achieve this goal.

It consists of two phases which are knowledge acquisition and data forwarding. During the first phase, each sensor node transmits a Hello packet, which contains their depth and residual energy to their neighboring nodes. The second phase involves the selection of the next hop forwarder to transmit the data packet from the source to the sink node. The next hop node candidate selected is a group of neighboring nodes with smaller depths than that of the sender node characterized by suitable residual energy. Briefly, this protocol contribution lies in the avoidance of high overhead and redundant packet transmission in an underwater wireless sensor network.

3.7.2 Protocol Design

During the knowledge acquisition phase, the sensor nodes collect the depth and the residual energy information of the broadcasting node to determine the one-hop forwarding candidates. It can be seen in Table 3.3 the HELLO packet structure used to share the depth and residual energy among nodes within communication range. To relieve the network from storing useless data, the HELLO packet is stored only by nodes with a shallower depth

Table 3.3: Format of the HELLO packet

Sender ID	Residual energy	Depth
-----------	-----------------	-------

than the source node itself. The residual energy comes into play to balance the energy consumption in the network. Due to the movement of the nodes, the submerged nodes update their HELLO packet on a regular basis.

Common knowledge that a hop-to-hop communication routing strategy in a network presents a great burden for the nodes located closer to the destination because of their direct connection-link to the sinks. This problem is addressed during the data forwarding phase of the EEDBR protocol. Basically, during a data packet broadcasting, the source node checks the HELLO packets of the qualified neighboring nodes and arrange them from the largest to the smallest residual energy value. Another important parameter to consider during this phase is the holding time T . It is computed as follow:

$$T = \left(1 - \frac{\text{current energy}}{\text{initial energy}}\right) * \text{max}_{\text{holding_time}} + p \quad (3.7)$$

Where, $\text{max}_{\text{holding_time}}$ is a system parameter (i.e., the maximum holding time a node can hold a packet), and p is the priority value [8].

The priority value, p , is used to avoid the transmission of the redundant data packet that might happen in the network due when multiple qualified nodes have the same residual energy level. The principle is to consider the depth of the forwarding nodes to form an ordered list and to initialize the priority value. The priority of each node is doubled as we go through the list index-wise. Therefore, nodes with the same energy level are prevented to transmit at the same time.

Figure 3.3 shows four different scenarios for the selection of the next forwarding node with neighboring in the communication area of the source node. In (A), node $n1$ and $n2$ are located at the same depth. However, node $n2$ has higher residual energy than $n1$ so it forwards the packet. In (B), both $n1$ and $n2$ have the same energy level. However, node $n1$ has a lower depth than $n2$ which leads to the selection of $n1$ as the next forwarding node.

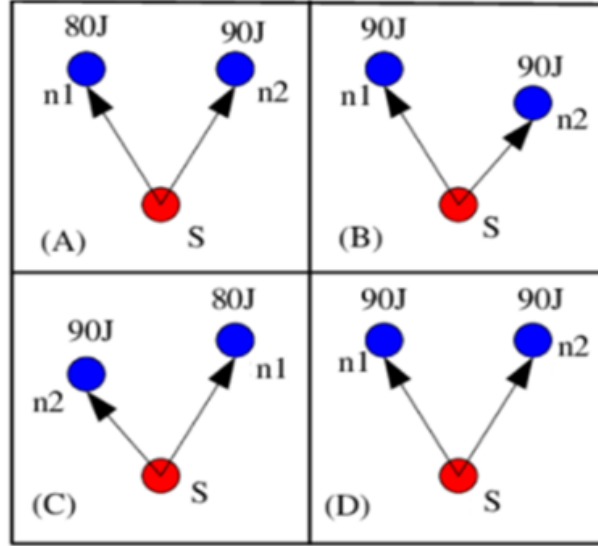


Figure 3.3: Next forwarding node selections in EEDBR

In (C), node $n2$ is located closer to the source than node $n1$. Based on the forwarding set selection of EEDBR protocol node $n2$ is the qualified node and to transmit the packet because its residual energy is higher than $n1$. In (d), it is possible that two or more nodes have the same depth and residual energy. In this case, the node is selected based on its priority value and holding time. Thus, the node with best holding time and priority value transmits the packets and the second one will drop the packets when overhearing the transmission of the same packets.

This protocol is also equipped with a mechanism that allows it to suppress the packet transmission when needed. During the holding time, upon overhearing the same data packet from another sensor node, the forwarding nodes generate a random number and compare it to the delivery ratio value received in the data packet. The nodes are clear to transmit if the random number is greater than the delivery ratio. Another scenario where a node with less priority can transmit is when its holding time expired and it did not overhear the same packet transmission.

3.8 Hydraulic-pressure-based Anycast Routing Protocol (Hydrocast)

In the forthcoming sections are presented the details of the hydrocast routing protocol.

3.8.1 Protocol Overview

Uichin et al. [14] proposed a specialized unidimensional geographic anycast routing to deal with the limitations of geographic routing. In hydrocast, a packet is forwarded to a node that has the lowest depth among neighboring nodes to the surface buoys (anycast mode). To determine their positive progress toward the sinks all the nodes must be equipped with a low-cost pressure sensor. The proposed scheme has two stages; the greedy routing and the void handling (recovery mode).

In contrast to the hop-to-hop strategy used in the previous protocols, the first stage of this protocol used a cluster-based approach to move the packet toward the sinks. Moreover, to reduce duplicate transmissions, the hydrocast algorithm employs a forwarding mechanism that enables the node with the higher progress in the subset of neighboring nodes (cluster) to transmit. If this node fails to transmit the packet the next node in line (progress-wise) will proceed. In the second stage, a void handling mechanism is introduced to take on the local maximum problem. In compliance with this mechanism, each local maximum node must find and store a recovery path to a node whose depth is lower than itself to resume packet transmission. This sets the stage for the description of the protocol design in the next section.

3.8.2 Protocol Design

As is well known, void avoidance is extremely difficult to control in greedy mode. Consequently, the opportunistic forwarding mechanism adopted in hydrocast represents a major contribution to the study. Before doing the analysis of this mechanism let's place a few words about the forwarding set selection methods adopted by the hydrocast authors.

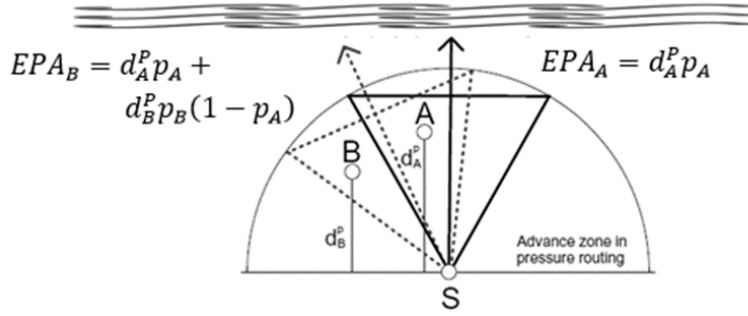


Figure 3.4: Impact of direction in pressure routing ($EPA_B > EPA_A$)

Initially, a subset of neighboring nodes is selected based on the packet delivery probability and the closeness of the nodes to the destination (maximum progress). Then the nodes existing in the area that covers half of the communication range of the source node are choosing to form a cluster. If other neighbors are left, clustering will start from the remaining nodes with the highest normalized progress. Next, the data packet forwarding prioritization process is scheduled with the use of a back-off timer which is set up proportional to the destination's distance [14]. The next equation to consider during the prioritization stage is the normalized sum of the advancements made by the neighbors. It's given as follows:

$$EPA(\Gamma_k) = \sum_{i=1}^k d_{n_i}^P p_{n_i} \prod_{j=0}^{i-1} (1 - p_{n_j}) \quad (3.8)$$

Afterwards each cluster is expanded by including nodes who can detect signals emitted from each sensor. The candidate nodes IDs are embedded in the data packet and broadcasted by each forwarder node. However, the packet whose IDs are not listed is simply removed. Finally, as shown in Figure 3.4, the Expected Packet Advance (EPA) metric is considered to prevent the nodes in the subset from redundant packet forwarding and solve the hidden terminal problem simultaneously.

Another key function of hydrocast is its recovery mode. It is recognized that there's no efficient recovery method in 3D networks. When a node cannot find any neighbor with a lower depth when compared to its own, greedy routing cannot be utilized; Thus, such node is regarded as a local maximum. As a means to tackle the void communication problem,

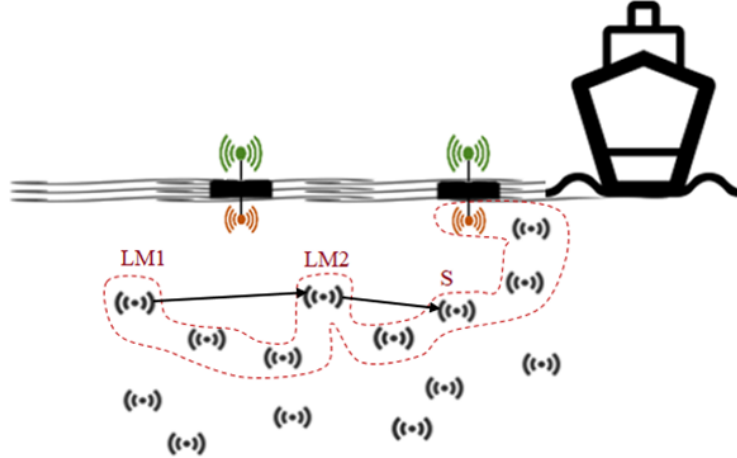


Figure 3.5: Recovery Mode

a local maximum recovery mechanism is utilized. Now the problem is that path discovery is still very expensive as it uses hop-limited 3D flooding.

The technique proposed is a unique approach where each local maximum builds an escape path to a node whose depth is lower. The idea is to only use the nodes located on the envelope or surface (nodes connected via the dotted red lines in Figure 3.5) for the path discovery. Now the challenge is to find whether a node is a surface node by using only local information. A node becomes a non-surface node if a node is surrounded by its neighboring nodes. After a few iterations, the data packet is routed to a node where the greedy mode is restored.

As seen from Figure 3.5, $LM1$ is a local maximum node which locates a detour path with a lesser depth to its own (i.e. $LM2$) and sends the data packet to such a node. Given that $LM2$ is a local maximum, it locates another node with a lower depth such as S and transmits their data packet. Once the data packet reaches a non-local maximum node, this node will send the data packet in greedy mode. Now the problem is that path discovery is still very expensive as it uses hop-limited 3D flooding. [14]

3.9 Geographic and Opportunistic Routing Protocol with Depth Adjustment for Mobile Underwater Sensor Networks (GEDAR)

Within the next sections is detailed the GEDAR protocol overview and design scheme.

3.9.1 Protocol Overview

Widely considered to be one of the most promising research fields in the networking area, the UWSN offers various applications allowing the monitoring and exploration of the ocean instead of a traditional wired network. In [10] the authors propose a new algorithm that combines geographic and opportunistic routing protocol strategy with the topology control technique based on depth variation. The selection of the next-hop forwarder set (cluster) is done according to the value of the depth of the neighboring nodes (packet advancement). If that value is greater than zero it means that the neighbors are in shallower water than the source and consequently is eligible to be part of the forwarding set. Otherwise, the node is ignored for further operations. Unlike the traditional geographic routing protocols that use the packet advancement to set the next-hop forwarders priority, in the paper the authors use a generalized link metric called: the normalized advance (NADV). During the prioritization stage, it takes also into consideration the time corresponding to the propagation delay of the packets.

Other major contribution of this paper lies in its unique recovery mode technique. Instead of the widely used message-based void recovery procedure, the methodology employed is a depth-based-adjustment topology control algorithm. When a forwarder node is trapped in a dead-end path it must inform its two-hop neighbors. Upon reception of that information, the two-hop neighbors send back to the void node their location information. Then the void node computes its new depth. Once the conditions are met the recovery mode will be put in sleeping mode and the greedy forwarding mode will be operational again.

3.9.2 Protocol Design

The Geographic and opportunistic routing protocol with Depth Adjustment for mobile underwater sensor networks (GEDAR), has two major phases: The forwarding set selection (enhanced beaconing and neighbors' candidate selection) and the recovery mode.

In the first phase, the authors describe an algorithm capable of sending data sensed at the subaqueous node level to floating sonobuoys. Prior to the data forwarding, is the enhanced periodic beaconing used to broadcast periodic beacons and handle received beacons [10]. In the GEDAR network, beacon messages consist of the component sequence number and its unique ID. In addition, the sonobuoys include their planar coordinates (X, Y location) in their packet while the submerged nodes embed their spatial coordinates (X, Y, and Z location) and the closest sonobuoy info in their own.

Before the transmission of a data packet, each node should determine a set of eligible neighbors to be the next-hop forwarder. Keeping in mind that GEDAR uses a greedy forwarding strategy, the source node must determine the difference between its depth and the depths of its neighbors. Based on these results the nodes- packet advancement- allowing the packet advancement towards the surface will be selected to form a cluster.

Following is the next-hop forwarder set selection which is characterized by three metrics namely the normalized packet advancement, the expected packet advance, and the propagation delay. The normalized packet advancement, also known as the normalized progress is simply the progress of a node ($d1$: vertical distance to the water surface) times the probability that node successfully receives the packet and it is revealed in equation 3.9. NADV corresponds to the optimal trade-off between the proximity and link cost to determine the priorities of the candidate node [10].

$$NADV_{n1} = d_{n1} * p_{n1} \quad (3.9)$$

Like hydrocast, this protocol also used the expected packet advance metric which is the summation of all the NADV of the one-hop forwarder nodes (equation 19). The neighboring nodes are arranged according to the node priority i.e. from the greatest NADV to the lowest

NADV. Now, the node with the greatest priority is selected with all the nodes which are located within half of the communication range of the neighboring set in question to form a cluster. The last step in the formation of a cluster consists of the addition of the other nodes that are within the range in the cluster. After the clusters have been formed, the algorithm will then select the cluster with the highest expected progress as the next-hop forwarder set. The equation given in 3.10 represents the last parameter of the forwarding set selection procedure described as the propagation delay of all packets from higher priority nodes. In GEDAR, when the node with the highest priority within the cluster is transmitting a packet the node with lower priority will suppress their transmission before to start broadcasting its own packet.

$$T_w^i = T_p + \sum_{k=1}^i \frac{D(n_k, n_{k+1})}{s} + i \times T_{proc}, \quad (3.10)$$

Where T_p is the delay needed for the complete propagation of the packet in the channel and T_{proc} is the packet processing time. the mathematical expression of T_p is defined as follow:

$$T_p = \frac{(r_c - D(n_a, n_b))}{s}, \quad (3.11)$$

where n_a is the current node, n_b is the node that broadcasts the packet, and s is the speed of sound in underwater.

In the second phase, Rodolfo et al. have addressed the common issue of the underwater acoustic sensor network protocols that use the greedy routing strategy. The tactics elaborated is based on a depth adjustment mechanism. When a node finds itself in a void are as a local maximum it sends out an acknowledgment packet to the previous two-hop forwarder and waits until those ones reply with their depth information. When the void node receives the information, it will keep the three-dimensional location data of those nodes and then determine its new depth from there. In other words, instead of message-based void node recovery procedures, GEDAR takes advantage of the already available node depth adjustment technology to move void nodes for new depths trying to resume

the greedy forwarding.

3.10 Void-Aware Pressure Routing for Underwater Sensor Networks (VAPR)

The VAPR protocol contributions to the underwater wireless sensor network are analyzed below.

3.10.1 Protocol Overview

In the Void-Aware Pressure Routing for Underwater Sensor Networks protocol, the authors present the design of an algorithm capable of handling underwater network while considering the unique submarine ecology. Like any other underwater network, the goal is to route the data packets from the ocean floor to the sinks. The problem with the greedy pressure routing strategy used in VAPR is the fact that it exposes the network to the local maximum problem in a sparse area due to the presence of void are. To overcome that problem, the development of a periodical beaconing message to identify the direction of each node is described in this paper.

The major characteristics of the VAPR protocol are twofold: 1) The enhanced beaconing and; 2) The opportunistic directional data forwarding. In the first scheme, every node initializes its beacon information before the start of the beaconing process. Each beacon contains information such as source node depth, hop count to the closest sonobuoy, sequence number, and its current data forwarding direction. Once a node receives a beacon it compares its information to the ones embedded in the beacon and updates its information accordingly. The direction is set upwards if the beacon is received from a node whose depth is less than the source node. Otherwise, it is set downwards. In the case where a node received beacons from different sonobuoys, the nodes with the minimal hop count are chosen. With the completion of its current state, the node will change its status from receiver to forwarder and start the forwarding process by incrementing the hop count,

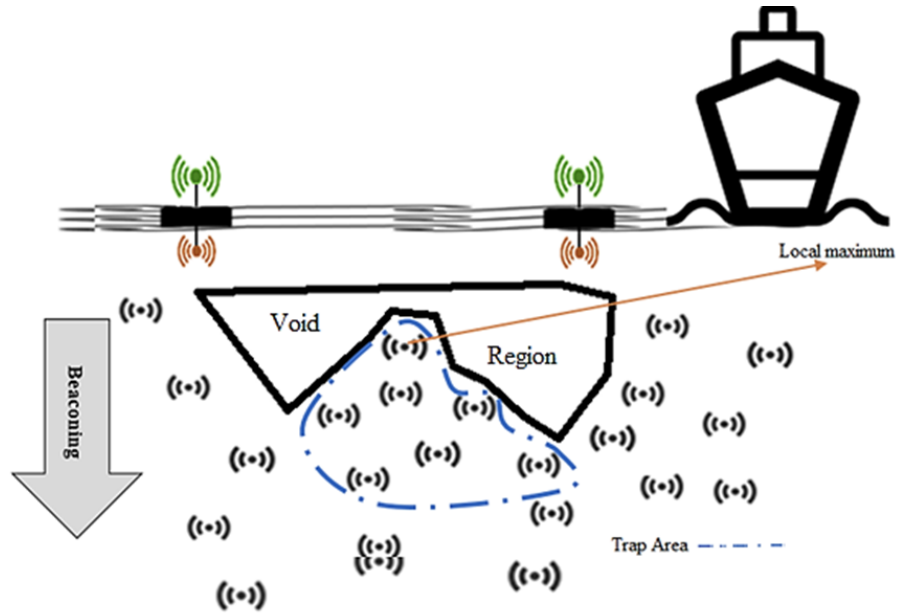


Figure 3.6: VAPR topology architecture

computing its current depth, decrementing the sequence number, and updating the data forwarding direction. However, this procedure will witness a considerable change when trapped in a void area. In Figure 3.6 can be seen an overview of the major subdivision of a typical VAPR network.

The opportunistic directional forwarding consists of the delivery of data according to the directional trails. During this phase two scenarios are possible: 1) if there is no void, packets can always be greedily routed via the upward direction, and we can solely rely on the data forwarding directions for routing; and 2) if there are voids, there will be direction changes, and the next-hop forwarding direction is jointly used with the data forwarding direction to guide the routing direction [15].

3.10.2 Protocol Design

The VAPR protocol does not approach the underwater network design as the above-mentioned protocols. In fact, contrary to start the broadcast from a submerged node to reach the surface, in VAPR the routing process starts from the sonobuoys and then make its way to the nodes located close to the ocean floor/ deep water. Therefore, ev-

ery reachable node in the network should be aware of the number of hops its broadcast packet will go through until it reaches a sonobuoy. To achieve that degree of awareness the authors proposed a modified version of the periodic beaconing of pressure routing by including sender's depth, hop count, data forwarding direction, and sequence number in a beacon message. Three algorithms are essential to comprehend the design of this protocol.

The first algorithm consists of the initialization of the underwater component status. The sonobuoys will set their data forwarding direction to up and their hop count and sequence number to 0. Regarding the underwater nodes, the data forwarding direction (DF_dir), next-hop data forwarding direction (NDF_dir) and the sequence number (SN) will be considered as null, the hop-count (hop_cnt) will have the value of 1. The sequence number will be increased at regularly occurring intervals; e.g., for instance, every 30s. In addition, each node stores their one-hop neighbors' depth, node ID, and data forwarding direction. Also, it is important to highlight that the information stored by each node are being constantly upgraded due to the mobility of the nodes.

The second algorithm represents an enhanced beaconing scheme proposed by Youngtae et al. in [15]. Upon the reception of a beacon message, the receiver nodes verify the validation of the received information by checking the sequence number and the hop count. The qualified next-hop forwarder is the one with the smaller hop count. Once the next-hop is chosen the receiver nodes must update their DF_dir and their NDF_dir .

Figure 3.7 is an illustration of the application of the enhanced beaconing strategy used in VAPR. After the initialization phase, since node a is directly linked to the sonobuoy and thus has lower depth, its beacon message will be upgraded accordingly i.e. the hop count will be incremented by 1, DF_dir and NDF_dir will be set as up. Similarly, the next-hop forwarder will continue with the selection process until the message reaches the intended destination. However, the direction of node e is downwards because it receives the beacon message from a node located deeper to its own position. During the selection process, when a node receives multiple beacon messages with the same sequence number; it uses the hop count to decide among them. If the hop counts are identical it then used a preferred direction (either upward or downward). The node i can be used as an example to

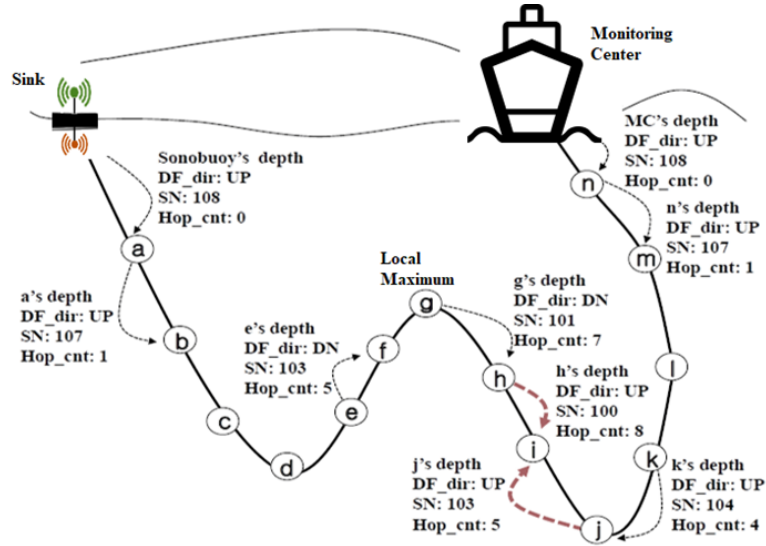


Figure 3.7: Enhanced beaconing in VAPR

illustrate the scenario when a node receives multiple cues from different directions. Node i has the option to forward its beacon whether towards node h or node j . Based on the second algorithm a node i must select the next-hop forwarder that offers the shortest path to reach the surface, in this case, node j .

In the third algorithm, the opportunistic directional data forwarding set selection, the goal is to broadcast the data packet toward the sonobuoys. In this algorithm, each node employs the direction information to forward the packet and avoids the communication void. This phase relies entirely on the data forwarding direction and the next-hop data forwarding direction. In addition, this algorithm employs a function that bears a close resemblance to the one proposed by Uichin et al in [14] called, *Clustering FSS* (F, node, data). The function is used to select a group of forwarding nodes among a source node one-hop neighbors and performs clustering to find the best cluster and to return a subset of one-hop nodes that can transmit the packet toward the sinks without the hidden terminal problem.

3.11 Summary

In order to set the topic in its context, the first section of this chapter highlighted the typical architecture, the applications and the challenges of an underwater acoustic network. Moreover, an analysis of the factors that affect the acoustic channel link quality and the mathematical models used to estimate them was described. In addition, a review of the preliminary works carried out in this field is conducted to distinguish the different approaches used in the design of an UWSN. The principle governing the Cross-layer protocols, the topology control protocols and the geographic routing protocols, and the issue they aimed to solve are highlighted. Moreover, the depth-based routing protocol, the energy-efficient depth-based routing protocol, the hydraulic-pressure-based anycast routing protocol, the geographic and opportunistic routing protocol with depth adjustment for mobile underwater sensor networks, and the void-aware pressure routing for underwater sensor networks are analyzed and described in detail.

Chapter 4

Performance Evaluation

This section focuses predominantly on the various parameters by which the implementation of the DBR, EEDBR, Hydrocast, GEDAR, and VAPR protocols has been conducted and the rationale for adhering to specific experimental procedures. It consists of three subsections. Section 4.1 discusses the simulation settings. Section 4.2 provides the description of the metrics used during the implementations. Finally, section 4.3 assesses the correlation between the above protocols substantiated by various graphs.

4.1 Simulation Settings

The software environment used to analyze the performance of the protocols was the free and open-source computer program *Ri3863.5.1* developed by the *R Core Team*. The size of the network area considered, is a three-dimensional region of $5000km$ wide, $5000km$ long, and $1500km$ deep. The planar dimension of the simulation is subdivided into squares of equal size in such a way the number of squares matches the number of sinks. In this paper, the implementation is conducted with 4, 9, and 16 sonobuoys which are localized at the center of each squares on the water surface. Expanding by steps of 25, the submerged nodes can vary from 50 to 250 and are randomly deployed at different depth within the predefined area. The topologies are formed when all of the combination possible of sinks and nodes are considered. We will go through different arrangements.

Table 4.1: Simulation parameters

Simulation Parameters	Values
Simulator	RStudio (R i386 3.5.1)
Deployment area	5 km x 5 km x 1.5 km
Transmission range	500 m
Energy consumption	$P_t = 0.8W, P_\gamma = 0.8W, P_i = 8mW, \text{ and } E_m = 15J/m$
Initial energy	5000 J
Frequency	14 kHz
Data packet size	250 bytes
Number of replications	50
Confidence band of CDR plots	95%

Each node has a maximum communication range of $500m$, a data rate of $18.7kbps$ and the initial energy is set to $5000J$. The data packet size of a node is fixed at $250Kb$. At a node level, the transmission, reception, idle and depth adjustment are the main operations that increase the energy consumption. The energy necessary for these operations are respectively $P_t = 18W$, $P_r = 0.8W$, $P_i = 8mW$, and $E_m = 15J/m$. The algorithms are executed 50 times for each topology i.e. an equivalent of 1350 runs in total. The confidence interval of 95% is considered for showing error bar in results. Table 4.1 summarizes the basic simulation parameters for the pressure-based routing considered.

4.2 Network Performance Metrics Description

In order to compare the techniques used by each protocol, measuring the network performance in different scenario is crucial. This entails the use of indicators (metrics) which are aimed to produce tangible figures. The metrics considered are the packet delivery ratio, the end-to-end delay, the number of hops and the expected number of hops. A brief overview of these metrics is given below.

- *End-to-end ratio*: Describes the successful rate at which any node randomly chosen from a topology can deliver a data packet. In other words, it takes into account all

the submerged nodes whether or not they are able to broadcast a packet.

- *Packet delivery ratio*: It is defined as the ratio of the number of distinct packets successfully broadcasted by a source node and the number of packets received at the sinks. It is important to mention that even if the sinks received the same nodes various times it only will consider a unique copy of the packet.
- *End-to-end delay*: Refers to the average amount of time taken for a data packet to travel across the network from a source node to any sinks on the water surface.
- *Expected number of hops*: Is a weighted average of all the possible values a number of hops can take. The basic idea is to multiply the number of hops of an end-to-end path to the probability of that path. In case of random variable, this technique is typically used to calculate the average.
- *Number of hops*: Represents the mean of number of hops forming a path for a given topology.

4.3 Simulation Results and Analysis

In this section, we analyze the results obtained for each scenario accordingly to the five metrics predicted. Our implementations proceed very much in the same way as described in each protocol respectively. We aim to examine the variations of the *CandidateSetSelection* of each protocol when increasing the number of sinks and underwater sensor nodes. Moreover, to identify the boundaries of this study, it is essential to understand that the sinks are deployed in a grid topology on the water surface. Meanwhile, the sensor nodes are randomly scattered over a subaquatic space equivalent to three trillion seven hundred fifty billion ($3.75 * 10^{10}$) m^3 . Table 4.2 compares the five routing protocols investigated in this paper based on features such as: the forwarding criteria, the void handling mechanism, the set selection procedures, the method of collecting data and the location information.

Table 4.2: Features of the selected routing protocols

<i>Protocol</i>	<i>Forwarding criteria</i>	<i>Void handling</i>	<i>Sender based/ Receiver based</i>	<i>Beacon based</i>	<i>Location based/ Location free</i>
DBR [12]	Depth	No	Receiver based	No	Location free
EEDBR [8]	Depth/Energy	No	Sender based	No	Location free
GEDAR [10]	Depth/Link quality	Yes	Sender based	Yes	Location based
Hydrocast [14]	Depth/Link quality	Yes	Receiver based	No	Location free
VAPR [15]	Depth/Direction/ Hop-cnt/SN	Yes	Sender based	Yes	Location free

4.3.1 End-to-end Ratio Comparison and Analysis

Figure 4.1 to Figure 4.4 indicates the performance of each protocol according to what we call in this report the end-to-end ratio. These metrics show the success rate for any given sensor node (connected or isolated) in order to deliver a packet to a sink. The values fluctuate between 0 and 0.15% which is very low. The main reason of this, is the result of the large simulation area chosen. In Figure 4.2 for instance, the topologies are comprised of four sinks and an increasing number of nodes. This scenario, reveals some irregularities with the EEDBR protocol which should be very similar to DBR when it comes to end-to-end ratio, with the exception of the timer mechanism it uses. Overall, we can see that a node chosen randomly have a slightly better chance to broadcast a message to a sonobuoy when implementing the DBR protocol.

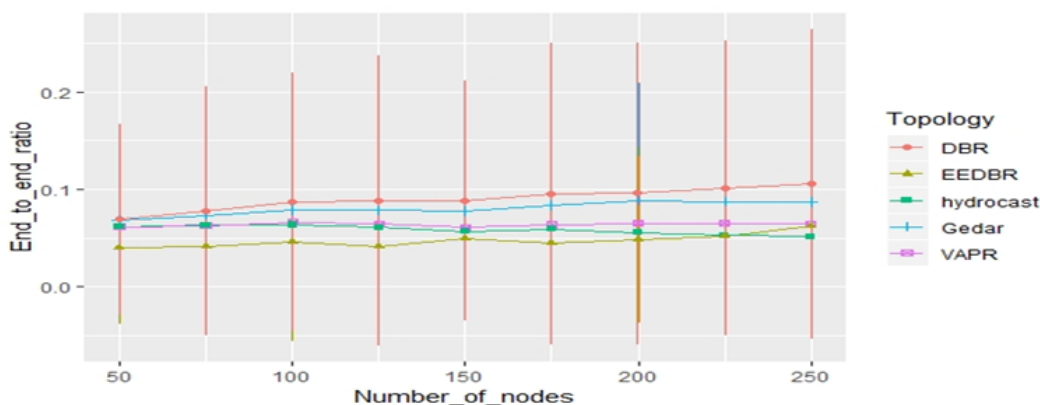


Figure 4.1: Average of the end-to-end ratio (%) for all the scenario

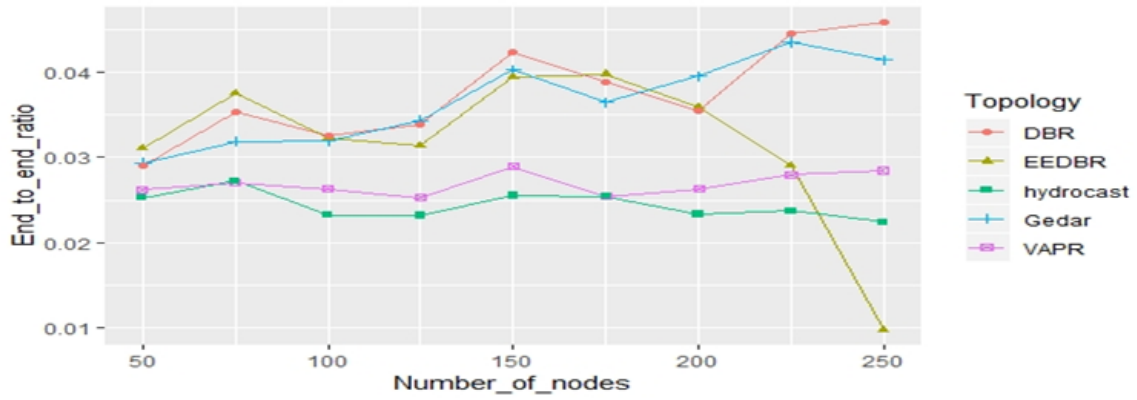


Figure 4.2: End-to-end ratio (%), scenario with 4 sinks

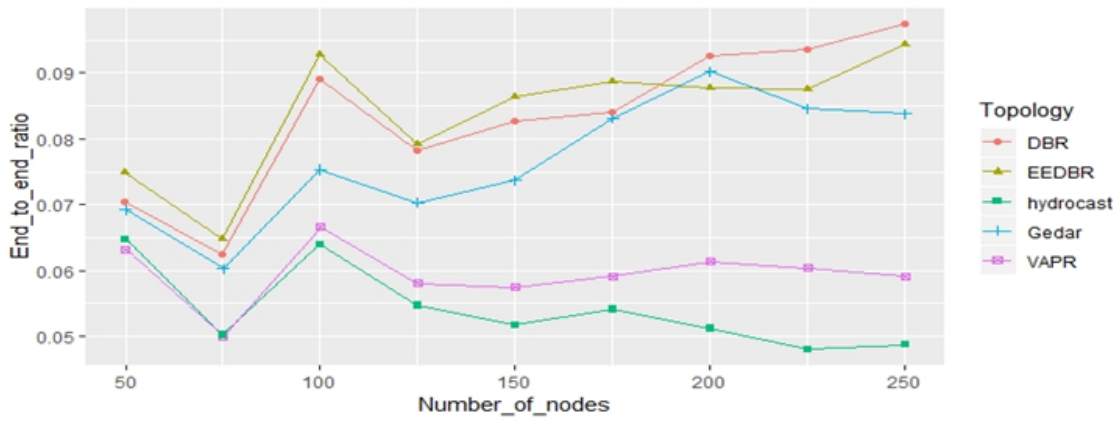


Figure 4.3: End-to-end ratio (%), scenario with 9 sinks

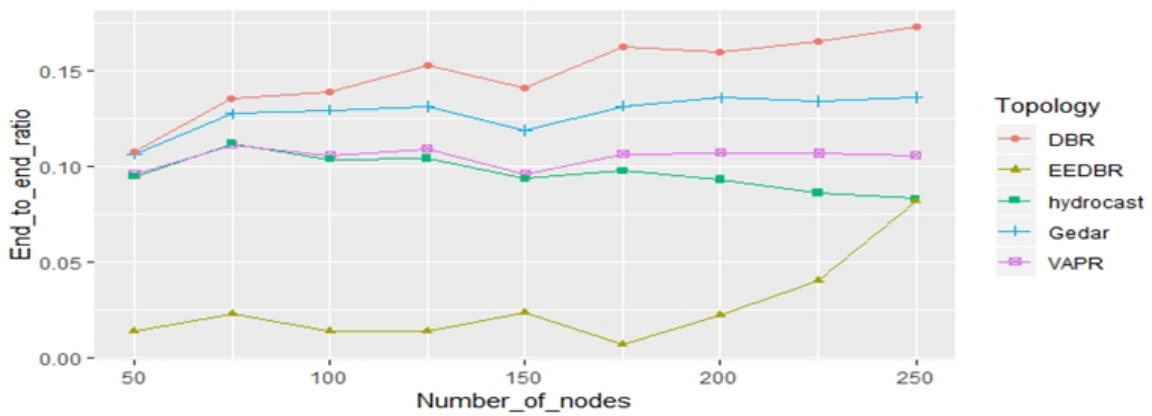


Figure 4.4: End-to-end ratio (%), scenario with 16 sinks

4.3.2 Packet Delivery Ratio Comparison and Analysis

Figure 4.5 to Figure 4.8 show the delivery ratio of the average of all the considered scenario. In the scenario with 16 sinks (Figure 4.8), all the protocols performed well with a delivery ratio enclosed by 95% and 97%. While the VAPR seems to have a constant delivery ratio regardless the scheme in play, the GEDAR has better results with the increase of the network density. The void handling technique used in those protocols definitely helps to improve their performance for these metrics as the number of discarded packet are minimized. Although, equipped with a void handling mechanism the test shows that hydrocast struggle against most of the other protocols. That is due to the void handling technique itself as it is required extensive communications with the neighboring nodes (two hop neighbors' information). Considering this fact, when the network is dense it will be exposed to packet collision and thus potentially reduce the delivery ratio.

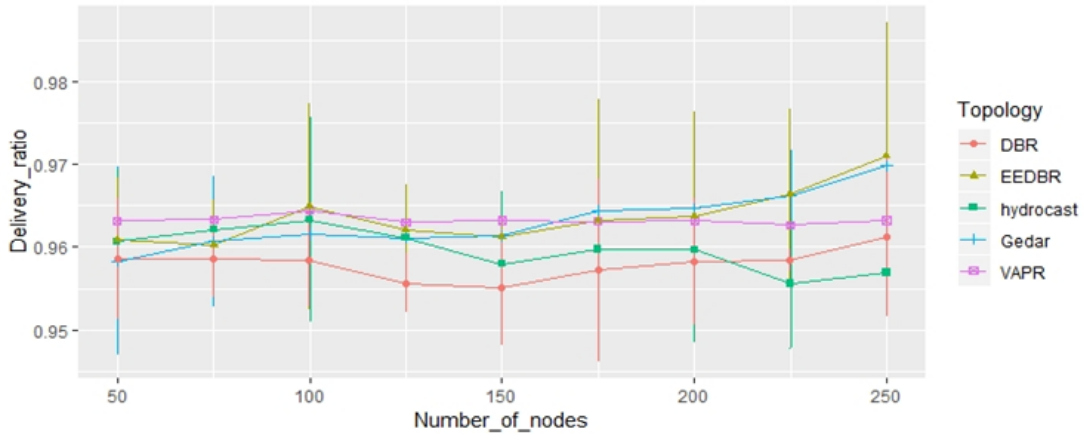


Figure 4.5: Average of the delivery ratio (%) for all the scenario

4.3.3 End-to-end delay Comparison and Analysis

Figure 4.9 to Figure 4.12, display the difference between DBR, EEDBR, hydrocast, GEDAR, and VAPR with respect to the end-to-end delay metric (latency). Here, the graph in Figure 4.11, shows clearly that EEDBR has the worst performance than the other protocols above all when the number of nodes increases. This is due to the timer mechanism it uses

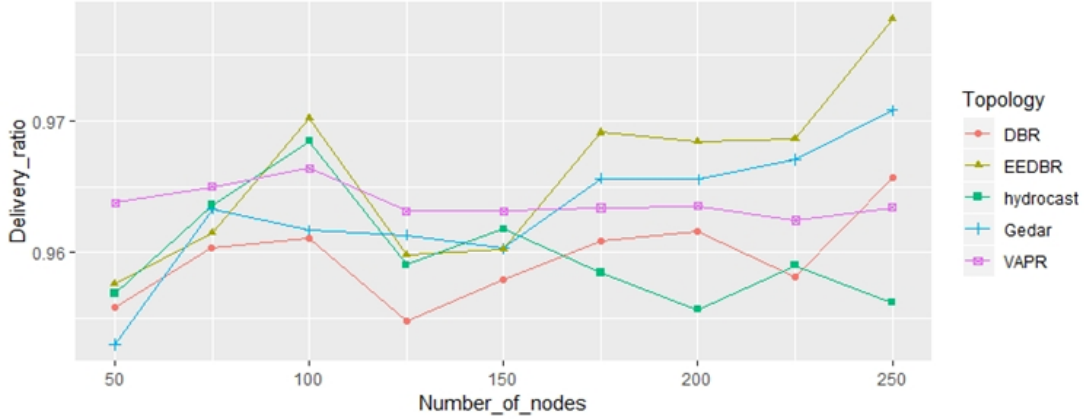


Figure 4.6: Delivery ratio (%), scenario with 4 sinks

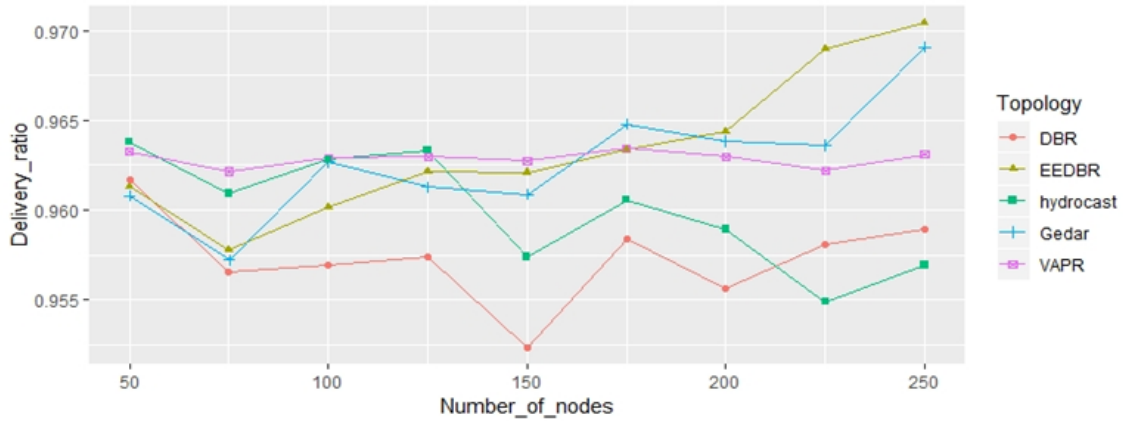


Figure 4.7: Delivery ratio (%), scenario with 9 sinks

to balance the sensor nodes energy within the network. In general, for any given topology relying only on greedy forwarding scheme, as the network density is increasing so is the end-to-end delay because the number of forwarding nodes will increase also. However, in this particular setup, the end-to-end delay varies approximately between 10 and 90 seconds for the other 4 routing protocols. The best in this category is without any doubt, the VAPR protocol due to its enhanced beaconing and opportunistic directional data forwarding. VAPR performance underlines just how important a forwarding set selection mechanism of a routing protocol can be.

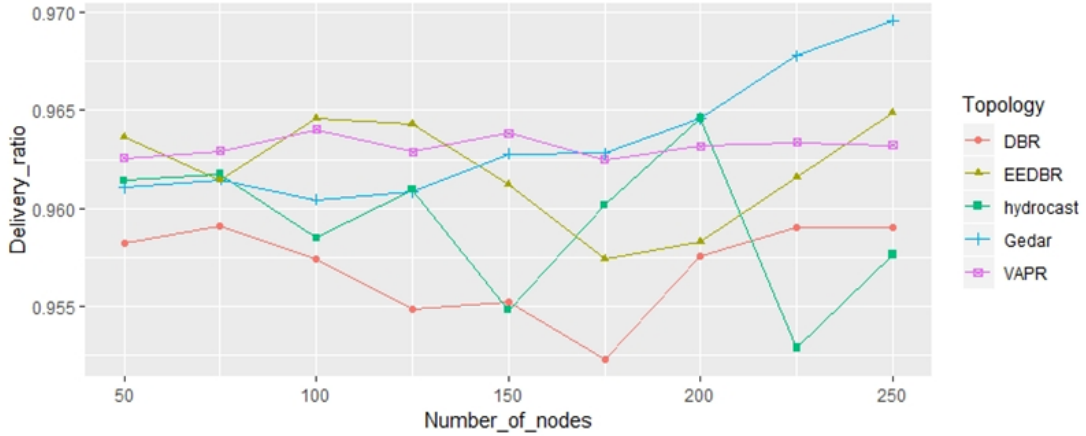


Figure 4.8: Delivery ratio (%), scenario with 16 sinks

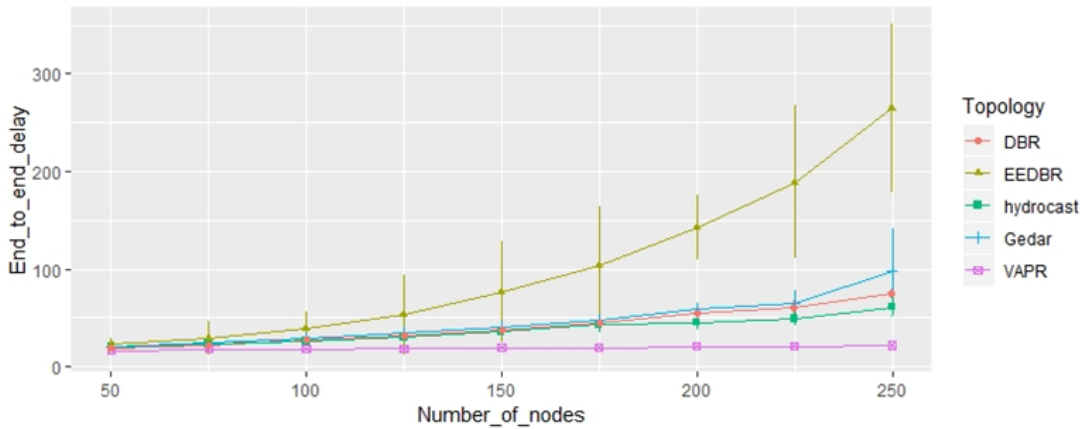


Figure 4.9: End-to-end delay (sec), for all the scenario

4.3.4 Expected Number of Hops Comparison and Analysis

The following 4 illustrations, compares the expected number of hops for each scenario. As expected, DBR and EEDBR use more hops to reach the surface because of the multiple paths forwarding technique where the packets are transmitted redundantly to reach the sink nodes. The other three remaining protocols require less number of hops because they used the clustering mechanism. It facilitates the localization of the route set up within the cluster and thus reduces the size of the next-hop information at the individual sensor nodes.

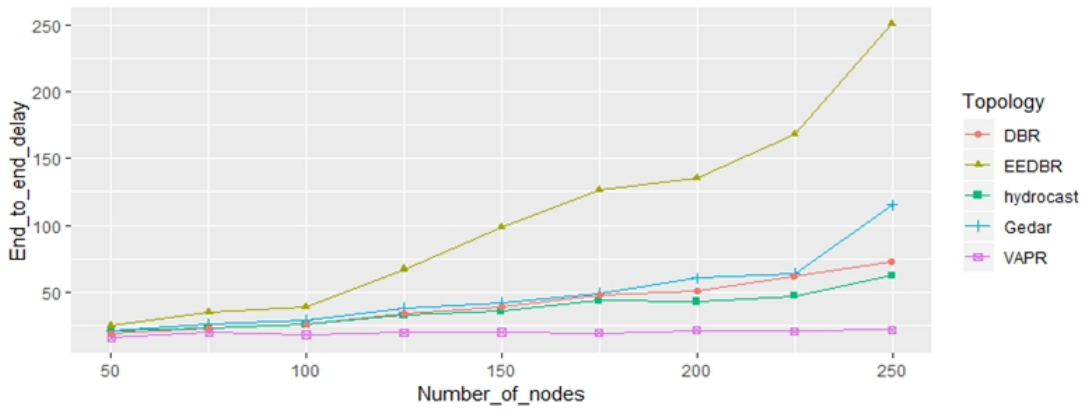


Figure 4.10: End-to-end delay (sec), scenario with 4 sinks

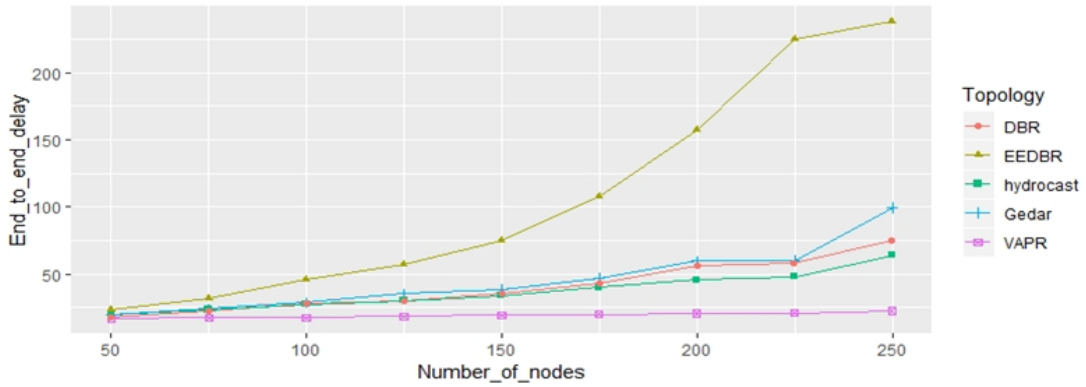


Figure 4.11: End-to-end delay (sec), scenario with 9 sinks

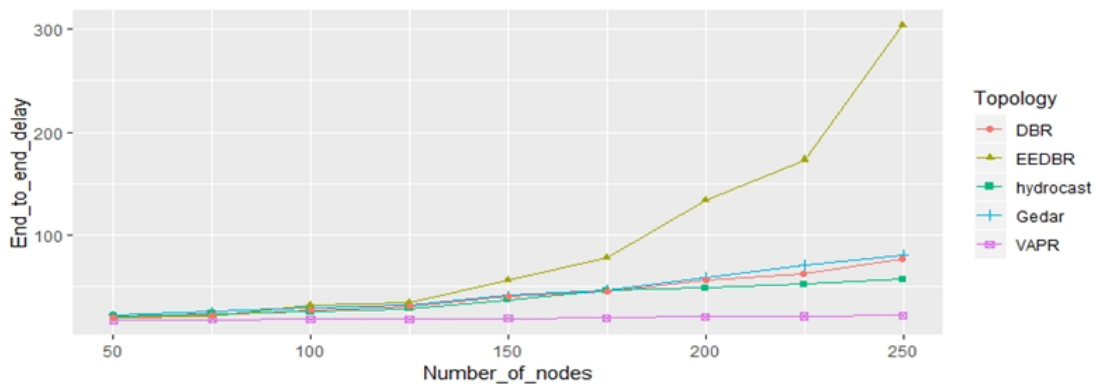


Figure 4.12: End-to-end delay (sec), scenario with 16 sinks

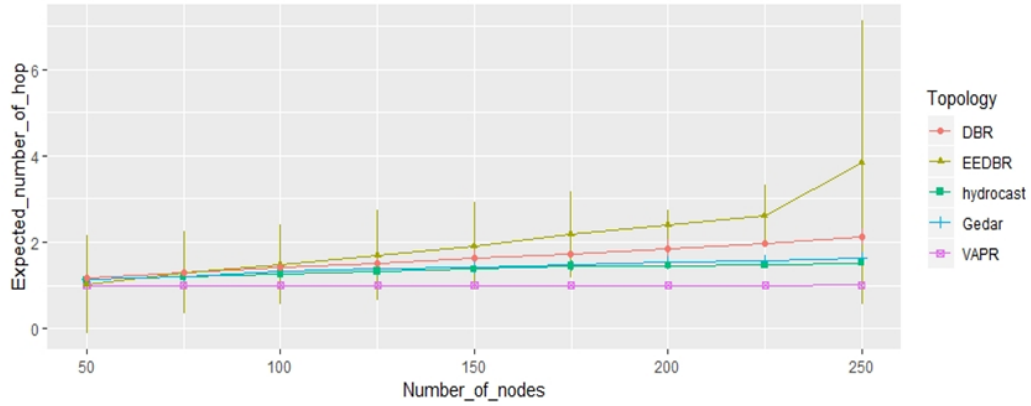


Figure 4.13: Average of the expected number of hops for all the scenario

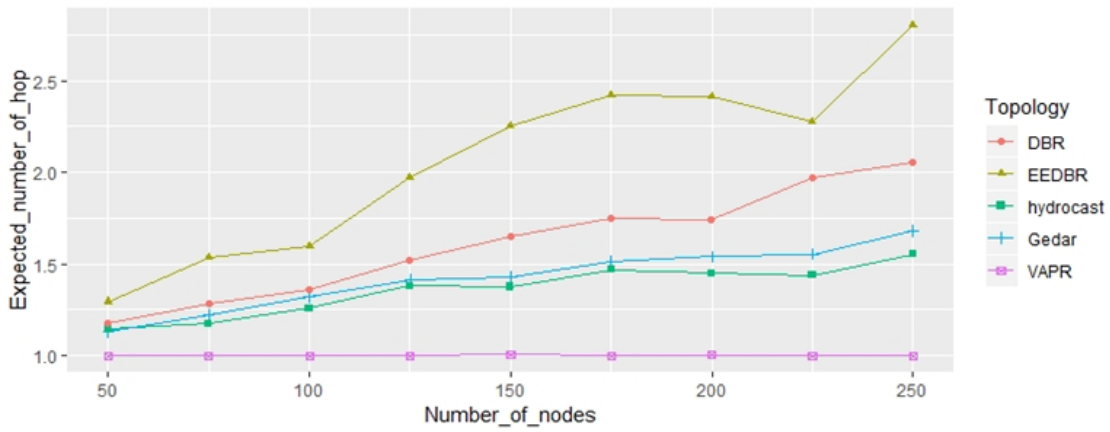


Figure 4.14: Expected number of hops, scenario with 4 sinks

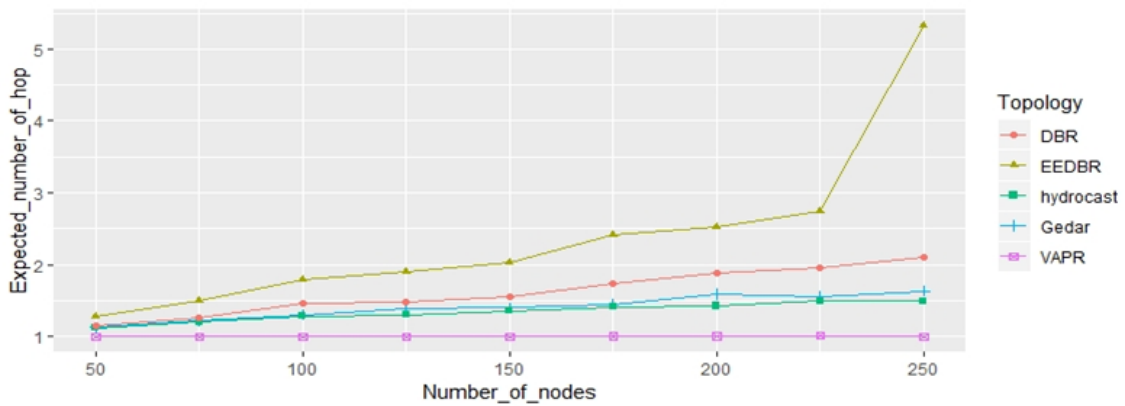


Figure 4.15: Expected number of hops, scenario with 9 sinks

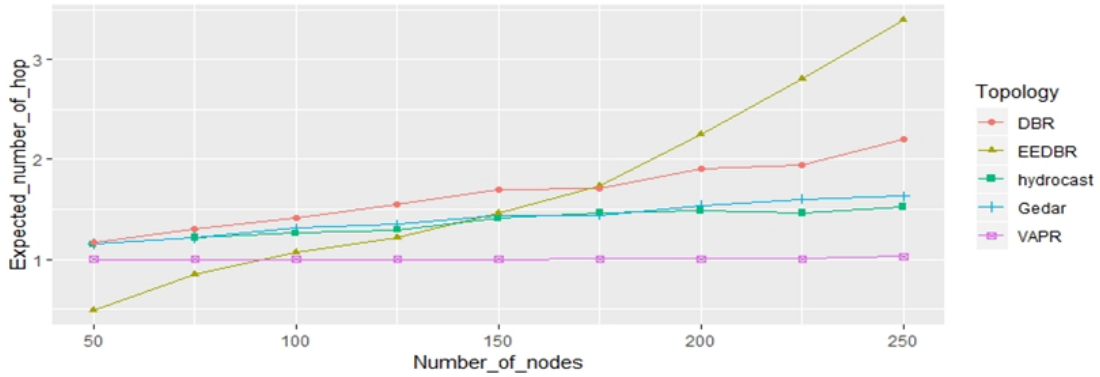


Figure 4.16: Expected number of hops, scenario with 16 sinks

4.3.5 Number of Hops Comparison and Analysis

Figure 4.17 to Figure 4.20 examines the number of hops required by each protocol to deliver a packet to a sonobuoy. The simulations show that VAPR outperformed the other protocols. This performance can be attributed to the network topology and the VAPR packet forwarding mechanism. The expected number of hops and the number of hops only differ by their application, otherwise they both are conceptually the same.

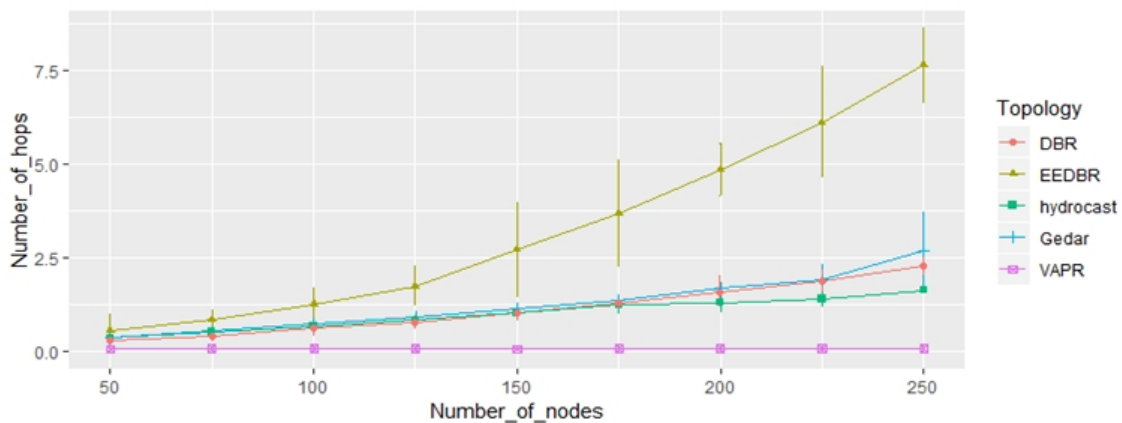


Figure 4.17: Average number of hops for all the scenario

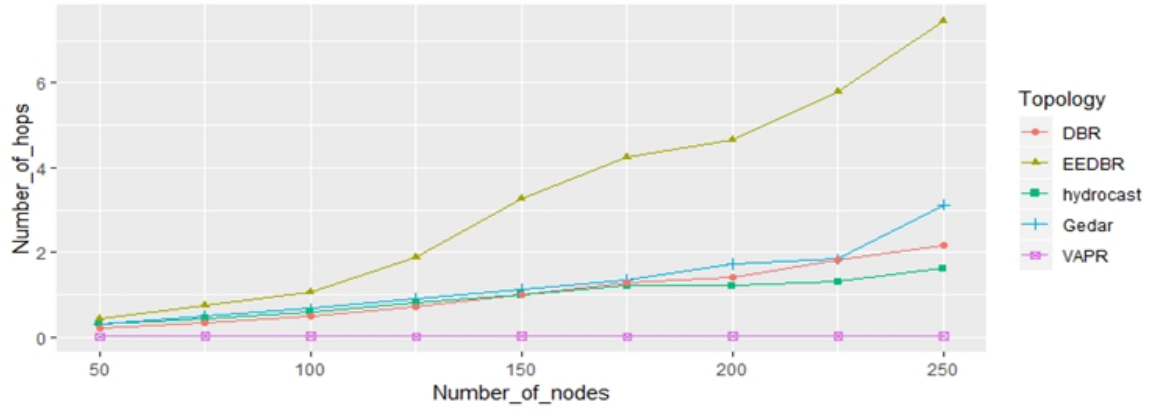


Figure 4.18: Number of hops , scenario with e sinks

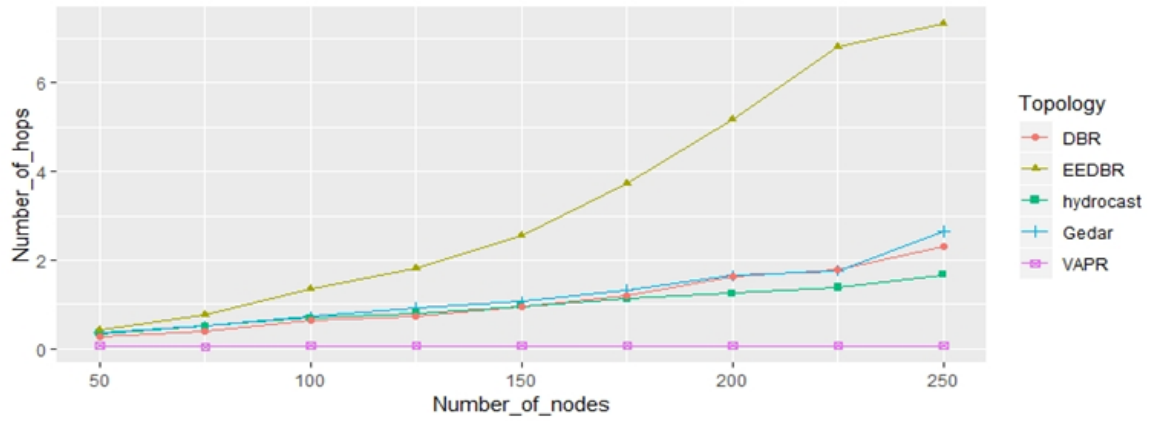


Figure 4.19: Number of hops , scenario with 9 sinks

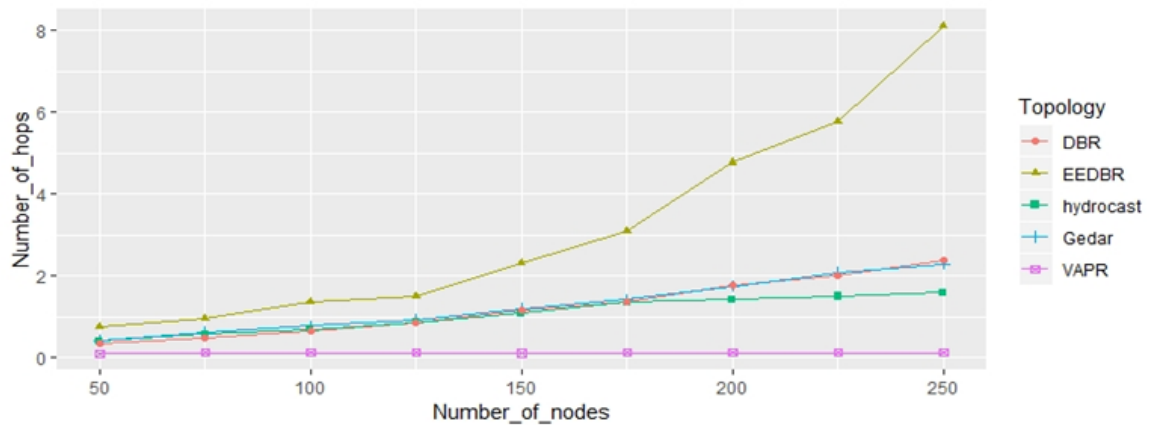


Figure 4.20: Number of hops, scenario with 16 sinks

4.4 Summary

In this chapter, the implementation of five state-of-the-art protocols is performed using a free and open-source integrated development environment RStudio. The results show that VAPR outperforms its competitions by reducing end-to-end delay, offering a heuristic method to handle the void area problem, and using a multi-sink structure. In addition, DBR, GEDAR, and hydrocast present satisfying results and perform practically equal as VAPR in a less dense network. However, extreme caution must be exercised in regards to EEDBR protocol, the results do not corroborate with previous results in [85].

Nevertheless, these results could contribute to a better understanding of the benefits and downfalls offered by each protocol and would further help in designing reliable, scalable and robust routing protocols for the underwater sensor networks. However, we aware that our research may have two limitations. The first is about EEDBR implementation, the second is regarding GEDAR and hydrocast void handling mechanism that was not been implemented properly. These limitations are caused by the difficulty of implementing wireless routing protocols using the *R* environment.

Chapter 5

Conclusion and Future Work

This chapter presents the recapitulation of the comparative studies carried out in this thesis in Section 5.1 Moreover, Section 5.2 highlight the potential directions that futures research works should validate based on our work.

5.1 Conclusion

In this thesis, we presented a framework for opportunistic routings (OR) in multi-hop wireless sensor networks (MWNs). We supported our extensive analysis with the description of several cutting edge papers. Moreover, the main contributions of this work were the implementation and the performance evaluation of five major protocols in underwater sensor networks (UWSNs).

Initially, we put the routing concepts into context. Then, we discussed in more details the characteristics and components of the OR scheme. By doing so, we identified three major components of OR which are: the metrics, the candidate set selection, and the candidate coordination. The metric component is further subdivided into hop-by-hop and end-to-end metrics. The candidate set selection comprehends to complementary phases which are the candidate prioritization and the candidate filtering phase. Lastly, the candidate coordination incorporates two distinctive techniques: the control-based and the data-based techniques.

Furthermore, we briefly introduced and categorized the different type of MWNs. We attempted to describe some key OR routing protocols that encompass the specificities of OR while considering their application in wireless mesh networks (WMNs), wireless sensor networks (WSNs) and mobile ad hoc networks (MANETs) respectively. We also classified these protocols according to relevant parameters identified in Section 2.8.

Next, the focus was set in the applications of OR in UWSNs. In the literature, there seems to be no general classification of the protocol designs resulting from this approach. In this paper we identified two categories, namely: multidimensional routing protocol and unidimensional routing protocol (pressure-based). The latter, according to the data forwarding technique employed, has been divided in its turn into two sub-categories which are the flooding-based packet forwarding strategy and the cluster-based packet forwarding strategy.

In order to set the topic in its context, the first section highlighted the typical architecture, the applications and the challenges of an underwater acoustic network. Moreover, an analysis of the factors that affect the acoustic channel link quality and the mathematical models used to estimate them was described. The review of the preliminary works carried out in this field was crucial to distinguish the different approaches used in the design of an UWSN. Lastly, we focused on the description and the detailed analysis of (DBR), (EEDBR), (Hydrocast), (GEDAR), and (VAPR).

Along with a meticulous examination, the implementation of the five protocols mentioned above was performed using a free and open-source integrated development environment RStudio. The results show that VAPR outperforms its competitions by reducing end-to-end delay, offering a heuristic method to handle the void area problem, and using a multi-sink structure. In addition, DBR, GEDAR, and hydrocast present satisfying results and perform practically equal as VAPR in a less dense network. However, extreme caution must be exercised in regards to EEDBR protocol, the results do not corroborate with previous results [86]. In order to implement all five protocols, we use a Microsoft windows operated machine equipped with an Intel i5-7200U 2.5 GHz with turbo boost up to 3.1 GHz, and 8 GB DDR4 memory. It took approximately 9 days to finish the simulation.

5.2 Future Work

As stated in the Introduction, our main aim was to revisit the details regarding the opportunistic routing protocols in MWNs and to evaluate the performance of five UWSNs protocols. Possible research on the topic in the future is proposed as follows.

- **Standardization of the opportunistic routing metrics.** After our investigations with exception of the expected transmission count (ETX) which is widely used most studies have used their custom metrics. Consequently, to evaluate two protocols we can not rely on the results presented in the associated papers.
- **Simulation tools complexity.** R offers a wide range of commands and allows powerful data visualizations. However, it is not designed specifically for network simulation and thus its utilization can become very slow and complex. Further investigation is necessary to validate certain aspect of routing protocols implementations.
- **Energy consumption analysis.** In our study, we did not evaluate the energy efficiency of the implemented routing protocols. It will be interesting to see if there is a variation in their performance when using R.
- **Void-handling mechanism.** Future studies should aim at the implantation of the void handling mechanism of GEDAR and hydrocast.

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