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Analysis and Optimisations in Depth-based routing for Underwater Sensor Networks

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Abstract

Underwater Sensor Networks (UWSNs) employ sensor nodes and acoustic communication to detect physical attributes of water such as temperature, pressure, etc. Research on UWSNs has emerged thanks to their wide spectrum of applications which includes the management of the oil reservoirs and the prevention of aqueous disasters, as well as military surveillance. The dynamic conditions of water, the energy constraints and the high error probability during data transmission are prominent challenges in the design of routing protocols in UWSNs. One of the main routing schemes is Depth-based routing (DBR) that performs a specialized anycast routing to the surface sinks, based along the depth measured from pressure sensors.

In this thesis, we study and optimise some routing protocols for UWSNs, specifically those based on DBR. To this aim, we designed a novel simulator for studying DBR and its enhancements. Our simulator is based on AquaSim-NG and NS-3 (Network Simulator). With respect to the state of the art, we implemented the cross-layer communication required by DBR and an accurate representation of the operational modes of acoustic modems with the associated energy consumption. We developed some analytical models for UWSNs with the aim of (i) identifying the optimal transmission range for sensor nodes given the state of the system, (ii) finding the optimal number of hops between the source and destination under various network settings, (iii) evaluating the role of the depth threshold in the definition of the routing scheme. In this work, a pivotal role is played by the energy consumption and expected lifetime of the network. Finally, based on our findings, we designed the Residual energy-Depth (RD) routing protocol which improves the network lifetime.

List of Publications

1. Mohsin Raza Jafri, Simonetta Balsamo, Andrea Marin, and Robert Martin, "Implementation of Depth-based routing and its enhancement in Aqua-Sim Next Generation for Underwater Wireless Sensor Networks", published in International Journal of Communication Systems, 2018, issue no. e3714, Wiley Online Library..

2. Mohsin Raza Jafri, Andrea Marin, Andrea Torsello, Majid Ghaderi "On the Optimality of Opportunistic Routing Protocols for Underwater Sensor Networks", accepted in the proceedings of 21st ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), 2018.

3. Kishor Patil, Mohsin Raza Jafri, Dieter Fiems and Andrea Marin, "Stochastic Modeling of Depth Based Routing in Underwater Sensor Networks", **submitted** in AdHoc Networks journal, Elsevier, 2018.

4. Simonetta Balsamo, Dieter Fiems, Mohsin Raza Jafri, and A. Marin "Analysis of performance in Depth Based Routing for Underwater Wireless Sensor Networks," accepted in the Proceedings of the 7th Workshop on New Frontiers in Quantitative methods in Informatics, InfQ'2017, December 5–7, Venice, Italy. Springer, pp. 18–31.

5. Mohsin Raza Jafri, "Adaptive Holding time and Depth-Based Routing for Underwater Wireless Sensor Networks," accepted in the Proceedings of the 11th EAI International Conference on Performance Evaluation Methodologies and Tools, VALUETOOLS'2017, December 5–7, Venice, Italy. ACM.

6. Mohsin Raza Jafri, S.Balsamo and A. Marin "Identifying the Optimal transmission range in Depth-Based Routing For UWSN," accepted in the In Proceedings of 31st European Simulation and Modelling Conference - ESM'2017, October 25-27, IST, Lisbon, Portugal. EUROSIS, pp. 288-292.

7. Kishor Patil, Mohsin Raza Jafri, Dieter Fiems and Andrea Marin, "Performance Evaluation of Depth Based Routing in UnderwaterSensor Networks", accepted in the proceedings of StochMod 2018 13-15 June, Lancaster University, UK.(Fast Abstract)

Preface

In this thesis, we have presented our research work published with Andrea Marin, Dieter Fiems, Majid Ghaderi, Simonetta Balsamo, Andrea Torsello and some other senior researchers. Some of the research work is still under peer-review process. I want to thank all of my co-authors, research group (ACADIA) members and Nicola Miotello for their support. I am thankful to my parents, my family, my friends specially Moid, Zeeshan, Kishor, Heider and Tahir for their support and guidance during difficult research phases. Moreover, I would like to thank prof. Riccardo Focardi, head of the doctorate school of Computer Science at the University Ca' Foscari. During these three years, we have provided an original and concrete research contribution related to the domain of underwater sensor networks (UWSNs).

The thesis consists of three main parts. The first part introduces the basic terminologies of acoustic communication, UWSNs and routing protocols in UWSN. It also explains the tips for routing protocol design for UWSNs and depth-based routing. The second part provides the literature review of network simulators for underwater communication. It discusses our original contribution related to the NS3-based underwater simulator, i.e., AquaSim-NG. The third part illustrates some probabilistic models that we proposed for a better understanding and optimization of the routing in UWSNs. Thanks to the observations that we derived, we have introduced some novel variations for the opportunistic routing protocols in UWSNs.

We organize the remainder of the thesis as follows. Chapter 2 introduces the basic terminologies of underwater communication and UWSN. It also explains the classification of routing protocols and the commonly used performance evaluation methods for UWSNs. Chapter 3 briefly explains the depth-based routing and its state of the art. It discusses the theory of routing metrics used in the classic depth-based routing schemes. Chapter 4 introduces our first contribution in UWSNs which is the design of NS3-based underwater simulator i.e AquaSim-NG. It also covers the thorough validation and experimental results of the simulator. Chapter 5, 6 and 7 introduce the stochastic models to optimize the routing metrics of depth-based and opportunistic routing protocols. Considering k-hop communication between the source node and the sink in terms of energy efficiency, optimal configuration have been identified. Chapter 8 defines a mathematical expression to find the optimal transmission range for the nodes in terms of packet delivery probability. Chapter 9 and 10 propose novel distributed opportunistic routing protocols in order to achieve an improved network lifetime and decreased energy consumption.

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Part I.

Preliminaries

1

Introduction

The importance of the oceans is mainly derived from their huge coverage area of the Earth's surface and the unexplored underwater resources. With the rapid growth of the Earth's population and the quickly decreasing terrestrial resources, the focus of the human research is increasing towards the marine environment. Apart from the primary underwater resources, transport and military importance of the oceans have also attracted the attention of the world superpowers in the last few decades. Although for a long time, seas have served mostly as a medium for business and transport, these have also defined the long-term military policies in the last century. The above-mentioned important aspects have led to a major development in the underwater research. Designs of large-scale underwater networks, underwater acoustic communication systems, fiber communication, and underwater sensor networks (UWSNs) are some of the major fields which have been acknowledged for their role in this arena of research.

Underwater communication system design is regarded as one of the most challenging fields of the marine research. In fact, in the design of a wireless underwater communication system, it is necessary to consider specific factors such as the Doppler spread and the signal scattering so that expensive hardware with strict requirements is usually required by large-scale networks. In order to design an effective communication technique, new protocols and electronic devices had to be devised since it is now always possible to bring the strong experience developed in the field of terrestrial network design to that of underwater ones. In fact, the conventional radio frequency (RF) communication techniques perform inefficiently in underwater scenarios due to their quick attenuation and signal absorption. The presence of shadow zones and the multipath effect also causes the deterioration of the signal as the speed of the acoustic signal varies with the depth and salinity of the water. These causes also result in temporary losses of connectivity among the underwater nodes. In order to tackle these issues, some of the novel communication schemes also use packet retransmissions aimed at improving the network throughput at the cost of a high network energy consumption.

The deployment of sensors to detect the physical attributes of the water defines the main ideology of UWSN. Although multiple ways of communication, e.g. optical fiber, acoustic and radio frequency (RF), are used for the monitoring purposes of the underwater environment, acoustic communication is considered as a more feasible and cost effective one. The applications of UWSNs exhibit the potential to improve the life quality of the future generations as these can support the human life in providing food and natural resources. Moreover, the continuous monitoring of oceans is crucial for understanding Earth's climate changes. Large scale marine applications such as seabed management, underwater pollution monitoring and sea mine detection require low cost network deployment, delay-sensitive communication and networks with reconfiguration capabilities.

The open challenges faced by the research in UWSNs include the reduction of the costs for hardware development, handling the frequent transmission losses, containing the error-prone underwater conditions and handling the continuous node mobility caused by ocean currents. Moreover, there is a requirement to deploy underwater vehicles and design of underwater localization schemes to assist the marine applications. Their inclusion in the UWSNs also comes up with the challenges, including the large energy consumption and the limited bandwidth capacity. Therefore, the deployment of low-power sensor nodes and simple yet efficient communication schemes are preferred over complex network infrastructures in UWSNs due to their non-feasibility in aqueous environment.

In this context, the design of routing protocol which are tailored to handle such specific conditions assumes a primary importance. Industrial and academic researchers have devoted large efforts in this direction, and have proposed several solutions.

In UWSNs, routing protocols ensure efficient data transmission between the deployed sensor nodes, underwater vehicles, mobile sinks and the on-surface sinks. Moreover, the data collected by the on-surface sinks is transferred to the onshore base station usually through RF or satellite communication. There are multiple classifications of routing protocols on the basis of various routing ideologies. Some of them include (i) Sender-based (ii) Receiver-based (iii) Opportunistic (iv) Depth-based (v) Localisation-based and (vi) Localisation-free routing protocols. These classifications are useful in the selection of the routing protocols considering the targets of the desired underwater applications.

The salient features of the classifications of routing schemes not only glorify their importance, but also point out the deficiencies. For example, opportunistic routing schemes improve the network throughput but increase the network energy consumption as they increase the possible number of forwarding nodes towards the sink. This capability makes them more suitable for the data-sensitive applications, e.g. underwater pollution monitoring. In the previous literature, there are several works related to the simulator design for UWSNs as they are useful for the performance evaluation of the newly devised routing protocols. A detailed survey on depth based routing and other opportunistic routing protocols can be found in [2]. One of the most widely adopted routing protocols for UWSNs is the Depth-based routing (DBR) whose implementation simplicity joint with its effectiveness are the main reasons of its popularity. The idea of DBR relies on a simple consideration: while in underwater networks we must consider a three-dimensional deployment of the nodes and hence the node localisation seems to be more challenging than what happens for terrestrial networks, we observe that it is possible to easily retrieve the location in one of the three dimensions, i.e., the vertical one. This can be done thanks to inexpensive pressure sensors installed in the network' motes. In general, the goal of the routing protocols in underwater networks is that of bringing the data harvested in depth to the ocean surface, where some sonobuoys will collect them and retransmit to the base station by means of RF communications. DBR widely exploits the depth information available to the nodes to design a routing toward the surface. Redundant transmissions are obtained thanks to a controlled flooding algorithm.

DBR is classified as a receiver-based routing protocol and implements the controlled flooding thanks to the idea of holding time and depth threshold. In other words, these mechanisms are aimed at controlling the number of retransmissions of the same packet by the sender's neighbours. The holding time is an idle period in which any node keeps the received packet in the sending queue before its retransmission. This is used to decide the data forwarder of a node-and depends on the depth difference between the sender and receiver. If during the holding time a node listens to the retransmission of the packet that is being hold in queue, then this is discarded according to the assumption that it has already been forwarded by a node with lower depth. The depth threshold is the minimum depth difference for the eligibility of packet forwarding node and is used to improve the protocol energy efficiency. Finally, the nodes maintain a packet history to avoid the retransmission of older packets.

Although there are a lot of simulators designed for underwater networks, there is also a need to study the performance of the well-known routing protocols by taking into account their peculiarities. In this thesis, we propose two novel variations of DBR, and also extended the its implementation in AquaSim-NG [3] in order to include a more accurate model of nodes' energy consumption. We take into account the operational modes of the acoustic modems which are installed to the underwater sensor nodes. Finally, we emphasized the cross-layer interactions between the physical and the routing layer. This allowed us to perform a comparison of several available protocols in terms of average energy consumption, connectivity and life-time. Finally, when possible, analytical models have been developed to compute the optimal parameters for the protocol given the network's density and the characteristics of the acoustic communications.

1.1. Thesis Statement

1.1.1. Research problem

In the last decade, UWSNs have been widely studied because of their peculiar aspects that distinguish them from common wireless terrestrial networks. In fact, most UWSNs use acoustic instead of RF based communications, and nodes are subject to high mobility caused by water currents. As a consequence, specialised routing algorithms have been developed to tackle this challenging scenario. DBR is one of the first protocols that have been developed to this aim, and is still widely adopted in actual implementations of UWSNs.

Due to the large cost of network deployment and scarse availability of the experimental resources, it is necessary to evaluate the performance of the classic routing schemes as well as to design the energy-efficient novel routing schemes for UWSNs basing the considerations on accurate simulation or analytical models. Moreover, there is a tough challenge to achieve an improved network lifetime along with a decreased end-to-end delay for long-term underwater monitoring applications.

1.1.2. Key idea

Several routing protocols are available in the literature on UWSNs, and all of them include a set of configuration parameters that depend on the characteristics of the deployments, such as, the water conditions that determine the loss probability of the transmissions, the node density, and the ocean currents present in the deployment area that characterise the mobility patterns of the motes. Clearly, is assessing the optimal configuration, simulations play a crucial role although they are time consuming and computational expensive to run. To this aim, in this thesis, we develop a novel simulator for UWSNs in order to evaluate the performance of depth-based routing protocols and its enhancements. With respect to the state of the art, our simulator in more accurate in handling the cross-layer communications required by DBR and in estimating the nodes' energy consumption. This latter factor is important to evaluate both the life-time of a single node and of the network. In fact, protocols that are unfair in distributing the workload among the motes cause a short life-time of the network which becomes soon disconnected. Unfortunately, DBR tends to suffer this problem, since the nodes closer to the surface tend to be more stressed than others.

Based on our simulator, we evaluated the performance of DBR and two variations that we propose to prolong the network life-time. Moreover, we devise three analytical models aimed at estimating some pivotal parameters of DBR's configuration given the network properties. The results that we proposed have been cross-validated with the simulations and allows the practitioners to partially configure the network without running expensive sets of simulation with the objective of optimising the network performance.

1.1.3. Objectives

As mentioned in the previous section, despite the large number of routing protocols that have been developed for UWSNs, there are very few analytical results that study their optimal configurations given the system's parameters (density of the nodes, frequency of transmission, etc.).

In this thesis, we aim to work in the field of analysis and simulation of routing protocols for UWSNs. During the initial phase, we contributed to the development of the field by implementing a new simulation tool for underwater networks. In the next phases, we concentrated on the performance evaluation of routing protocols of UWSNs by devising some new stochastic models that allow for a better understanding of the dynamics of underwater routing protocols, specifically for what concerns their performance. Du ring our research, we also intend to identify the optimal configurations of the routing metrics for depth-based routing by designing the probabilistic model.

1.1.4. Contribution

[1] Design and implementation of a new simulator for (UWSNs)

In this work, we have studied the state of the art of the simulation tools for UWSNs with particular attention to those based on the Network Simulator (NS), which is the most widely used tool in the networking community. We have developed a new tool, based on Network Simulator (NS), which extends the previous Aquasim-NG in order to encompass a detailed model of the energy consumption of underwater sensors. Specifically, the management of the modem's working phases and an accurate implementation of the interference models makes this tool a valuable instrument for the performance evaluation of UWSNs. Moreover, we propose a novel routing protocol Residual energy-depth (RD) based protocol which improves the network lifetime as compared to state-of the-art protocols. The tool has played a central role in our research activity and is used to validate the stochastic models that we propose in our publications. This research work has included Dr. Robert Martin from the University of Connecticut, USA.

[2,3] Analysis of performance in Depth-based routing for UWSNs

Despite its simple formulation, the correct functioning of DBR depends on a set of configuration parameters whose values are not easy to estimate by using stochastic simulation. Although DBR is widely adopted for actual UWSN implementations, in the literature there are very few models for its analysis, and hence finding the optimal parameter sets is a hard task. In this work, we have worked to partially cover this gap by proposing a set of analytical models that allows the efficient computation of the performance indices of networks employing DBR. In particular, the proposed model aims at determining the optimal transmission power for DBR networks by studying the trade-off between the energy consumed for a certain transmission range and the number of retransmissions required to reach the sink. This research work has included prof. Dieter Fiems from the University of Ghent, Belgium. In [3], the same problem is addressed by using stochastic simulations.

[4] Adaptive Holding time and Depth-based (AHT) routing protocol for UWSNs

In this work, we propose a routing scheme to parameterise the protocol configuration that depends on the local conditions of each node, in particular on the number of perceived neighbours. Simulations show that the solution helps in controlling the energy consumption of the network while reducing the end-to-end delay of the packets.

[5] On the Optimality of Opportunistic Routing Protocols for UWSNs

The model introduced in this work proves that the optimality of opportunistic protocols can be reached by introducing a threshold on the eligible forwarders of a packet. The work gives a computational method for deriving this threshold and studies the trade-off between packet delivery ratio and expected number of forwarders for each transmission. We think that the deployment of UWSNs using DBR can take great advantage from this result since the depth threshold is a key-parameter that characterises the protocol definition. This work follows from the collaboration with Prof. Majid Ghaderi of the University of Calgary.

[6,7] Stochastic Modeling of Depth-based Routing in UWSNs

Finally, the works proposed in [6] and [7] are the outcomes of the research mobility in Ghent. These works propose the probabilistic models where node mobility plays the central role. The models allow the analysis of the impact of mobility on some relevant performance indices including the packet delivery ratio and the energy consumption. Both the models of [5] and [6] have been validated with simulations performed in NS3 based AquaSim-NG. The research work has included prof. Dieter Fiems and Kishor Patil from the University of Ghent, Belgium.

1.1.5. Publications

1. Mohsin Raza Jafri, Simonetta Balsamo, Andrea Marin, and Robert Martin, "Implementation of Depth-based routing and its enhancement in Aqua-Sim Next Generation for Underwater Wireless Sensor Networks", published in International Journal of Communication Systems, 2018, issue no. e3714, Wiley Online Library..

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2

Underwater Sensor Networks: Basic Concepts

On June 1, 2015, China faced the deadliest maritime disaster in its history [4] when a ship was traveling with 454 people onboard in the Yangtze river. A massive thunderstorm capsized the ship and caused its complete destruction. About 442 people died and only 12 had been rescued. After facing the gusts over 118 km/h, the ship sank in approximately 15 meters deep waters. It took about 12 hours to provide full-sized rescue support to the ship and even 30 days to identify the accurate number of rescued people. One of the major reasons for the disaster seemed to be the delay in the notification of the thunderstorm to the technical staff of the ship. This kind of incidents reminds us repeatedly of the importance of aquatic research including the design and analysis of underwater acoustic communication systems.

2.1. Introduction to Underwater Wireless Sensor Networks

The advancement of underwater communication is necessary for the scientific research community as oceans cover the 70 percent of the Earth's surface [5]. Presence of oceans, seas, rivers, and lakes drives the major aspects of our daily life since it provides an effective medium for commerce and transport. According to [6], about 95 percent of the volume of the oceans is unexplored, thus leaving huge scope for improvement in research. In the past hundred years, most of the research related to underwater communication has been mainly done for military purposes during the world wars. There are three main ways of communication in underwater networks, which include acoustic, radio-frequency (RF) and optical communication. Due to its intrinsic characteristics, researchers prefer acoustic signal for the underwater communication as high-frequency electromagnetic waves confront extreme challenges caused by the aqueous environment. The optical fiber is also considered as a possible medium of communication, but it has its own constraints that include high scattering and large deployment cost due to the large coverage area requirement of underwater networks. Major discoveries developed in underwater research were made after the proposal of the passive sonar equation [7] which models the channel loss in the underwater communication.

In the last few decades, Underwater Wireless Sensor Networks (UWSNs) have emerged as an important topic for aquatic research [8, 9] thanks to their numerous applications in the management and surveillance of the underwater environment. Significant examples of these applications include the management of oil reservoirs, sea mine detection, prevention of aqueous disasters, etc. UWSNs usually consist of onshore base stations, several sinks which float on the surface of the water and a generally higher number of nodes equipped with sensors which stay underwater at various depth levels. Nodes sense the physical attributes of the aqueous environment while on-surface sinks collect the data from the nodes and transmit it to the onshore base station for further processing. Underwater vehicles assist the nodes in performing their operations. The usage of remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs) depends on the requirements of applications.

Acoustic communication [10] is widely adopted in underwater environments because of their two major properties. First, it faces low signal interference due to its longitudinal nature. Second, it can travel to a large distance due to its very low frequency while high frequency signal is absorbed in the water quickly. Large transmission coverage of thousands of meters allows for an efficient deployment of UWSNs. Figure 2.1 shows the

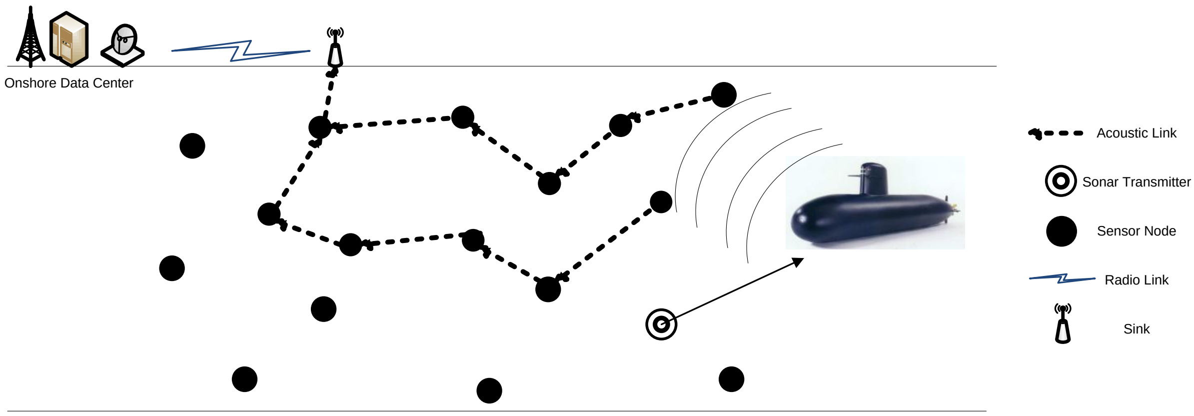

Figure 2.1.: Submarine detection using UWSNs

application of UWSN in which nodes are used to detect the presence of a submarine in the water.

In the design of UWSNs, we have to account for some aspects that are crucial for their correct operation:

Containing the energy consumption: UWSN nodes are powered by a battery whose replacement is particularly challenging. Therefore, one of the major aspects that we have to consider when we evaluate the performance of a protocol is its expected energy consumption and if it has the capability of balancing the energy consumption among the nodes.

Reacting at node movements: Wave motion makes maintaining permanent routes in the underwater environment extremely difficult. Therefore, protocols such as the adhoc on-demand distance vector (AODV) [11] that search for a route and then maintain it for a long time are not applicable in general.

Limitations on available bandwidth: Underwater communication poses some severe limitations on the available bandwidth that is much lower than the one available for terrestrial electromagnetic RF based networks.

Large transmission delay: The propagation speed of the acoustic signal in aqueous environment varies from 1450 to 1500 m/s which causes an increased transmission delay. It poses serious challenges for the delay sensitive applications, e.g., seismic monitoring and flood detection etc.

Among the major peculiarities of UWSNs, our emphasis is on the power consumption of the acoustic modems which is much higher than the one consumed in terrestrial wireless communication. Moreover, nodes are susceptible to frequent unpredictable movements due to the wave motion. As a result, the design of algorithms for UWSNs can significantly differ from those proposed in terrestrial Wireless Sensor Networks (WSNs) and the simulation tools must account for the factors that in the terrestrial scenarios may be neglected (e.g., the propagation delay of the packets).

In the previous research, several efforts such as improvements in the design of sonar equipments, underwater localization strategies, node deployment schemes, underwater communication architectures and utilization of underwater vehicles have been shown to be tackling the challenges of underwater communication. An advanced node design can increase the sensing range and provides high data processing capabilities, but it requires complex circuits and high energy consumption which reduces the lifetime of the sensor node. To mitigate this problem, some of the UWSNs consider energy-harvesting techniques and they depend on the natural marine resource, *i.e.*, wave movements and metabolic activities of bacteria, etc.

Network localization is one of the major challenges in underwater communication, which is tackled through various techniques, e.g., offline localization schemes, satellite communication and Global positioning system (GPS). In the large-scale underwater networks, satellite communication and GPS are also considered as a viable solution for identifying the location of deployed nodes. However, these techniques are very expensive to implement both in terms of hardware cost and of energy consumption.

In fact, the transmission equipment required for satellite communication and positioning is expensive and its energy consumption is prohibitive in an environment where battery replacement is almost impossible. To some extents, offline localization techniques, based on message passing may seem a viable approach. However, also in this case, the energy consumption due to the overhead induced by the exchange of the messages required by the protocols becomes a major limitation. In conclusion, we can say that the most effective and used routing protocols for UWSNs are localization free, *i.e.*, are unaware of the location of the nodes at a certain time.

Recently, the underwater vehicle design has been introduced as one of the most important areas of aquatic research, due to its extremely useful potential for the applications. Multiple types of underwater vehicles include courier nodes, remotely operated vehicles, autonomous underwater vehicles and underwater robots, etc. Some of them can control their 1-dimensional vertical movement while others have the capability to control their 3-dimensional movement. Courier nodes are often used to collect data from the nodes at various depths and they can only control their vertical movement. ROVs are useful for the disaster monitoring applications as their mobility patterns can be changed according to the environmental conditions. For the long-term monitoring, AUVs are preferred as they can control their 3D movement without the permanent input from the onshore base station.

2.1.1. The role of acoustic communication

Due to the longitudinal nature of sound waves, the aquatic medium assists the acoustic signal in covering the distance of kilometers, which is quite helpful for long-range marine communication. In contrast, RF signals face high attenuation and doppler spread in the underwater environment due to their transverse nature.

The phenomenon of the movement of particles of the acoustic signal is explained by the wave equation [12]. It can be modeled by the mathematical expression computing the displacement of sound particles in the liquid medium. Although the above-mentioned characteristics of the acoustic signal are useful for long-range transmissions, however, lower frequency and bandwidth issue restrain a high transmission data rate. As a result, the data rate of the acoustic signal is restricted to few kilobytes per second [13], which is quite low as compared to RF communication. The quality of the signal is also deteriorated due to other factors of underwater environment such as temperature, turbulence, salinity, and shipping noise etc.

RF communication is not used in underwater networks as high frequency signal faces severe fading, non-guassian noise, doppler spread and strong attenuation. The salient features of acoustic communication make it capable of handling the above-mentioned issues in an efficient way, although it still faces the challenges of high power consumption, low bandwidth and large end-to-end delay. Moreover, underwater networks are different in many aspects from the terrestrial networks. For example, energy consumption is higher due to the longer distance covered by acoustic signals and the complex signal processing. Since communication speed is equal to the speed of sound (*i.e.*, 1500 m/s) [14], the propagation delay is also much higher than of terrestrial networks.

The transmission power consumption of an acoustic signal in UWSNs is computed by the passive sonar equation presented in [15]. It calculates Signal-to-Noise Ratio (SNR) at the receiver based on some parameters among which the transmission power and the absorption loss play the major roles. SNR is computed as follows [16]:

$$SNR = SL - TL - NL + DI \tag{2.1}$$

where SL is the source power level, TL is the transmission loss, NL is the total noise loss, and DI is the directivity index. In this equation, all the quantities are measured in $dbre\mu Pa$ where the reference value of $1\mu Pa$ equals to $0.67 \times 10^{-18} Watts/m^2$ [16]. We use the notation dB to signify $dbre\mu Pa$.

The absorption loss of the acoustic signal is computed according to the well-known Thorp's formula [15]:

$$10\log_{10}\alpha(f) = \begin{cases} 0.11f^2/(1+f^2) + 44f^2/(4100+f) + 2.75 * 10^{-4}f^2 + 0.003, & \text{if } f \geq 0.4 \\ 0.002 + 0.11(f/(1+f)) + 0.011f, & \text{if } f < 0.4 \end{cases} \tag{2.2}$$

where f is the frequency measured in kHz and $\alpha(f)$ is measured in dB/km.

The transmission loss TL is computed by combining the total absorption loss $\alpha(f)$ and the spreading loss:

$$TL = 10\log A(l,f) = k * 10\log(l) + l * 10\log(\alpha(f)), \tag{2.3}$$

where l is the Euclidean distance between the sender and receiver, and k is the spreading coefficient.

The noise model consists of four main components: the wind factor ($N_w(f)$), the shipping factor ($N_s(f)$), the thermal factor ($N_{th}(f)$) factor and the turbulence ($N_t(f)$) factor which are defined as follows:

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

where s is the shipping constant and its value varies from 0 to 1. w is the wind constant having a positive value which shows the speed of wind. A discussion about practical values assumed by these constants can be found in [15]. Finally, to compute the total noise loss NL we combine these components:

$$NL = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{2.4}$$

Notice that the transmission frequency (f) dominantly affects the level of noise as higher frequency tends to increase the noise loss of signal.

2.2. Routing protocol design for UWSNs

As mentioned previously, routing protocols mainly aim at providing high network connectivity, low energy consumption and low packet delay by capitalising the intrinsic characteristics of acoustic communication. From the functional point of view, routing protocols transmit the sensed data collected by the underwater nodes to the sink nodes on the surface, which eventually transmit them to the base station for further processing. Underwater nodes are usually equipped with batteries which are difficult to replace or recharge and for this reason energy preservation is a key-factor in the design of routing algorithms and a simple flooding strategy turns to be highly inefficient. In the literature, several strategies have been proposed in order to introduce new routing protocols or to optimize previously proposed protocols, including specific node deployment strategies, localization schemes and transmission range selection. The dynamics of the wave motion, the energy constraints of deployed nodes and the high transmission error probability are also the prominent challenges in the design of efficient routing protocols in UWSNs.

2.2.1. Localization and reliability issues

There are many challenges in the design of routing protocols at the network level which are considered crucial in achieving a high quality of service in underwater applications for which lots of attention is required. Among these challenges, the 3D mobility of nodes induced by the wave movement is very critical. The result of this movement is the continuous change in location information of the devices deployed in the underwater environment, even if they are tied through sonobuoys or on-surface vessels. The continuous mobility of the nodes makes the application of fixed path transmission between the source and the destination nodes unfeasible. In fact, the data routing paths are usually broken and a new path formation is required after a small duration of time. This phenomenon explains the incapability of the usage of terrestrial communication schemes in underwater environments. Localization schemes are designed to find and continuously update location information of nodes; however, they have a high energy cost due to redundant transmissions. Some of the previously designed localization schemes employ clock synchronization and reference nodes to solve this issue as the nodes predict the change in their location information by communicating with each other.

Erol et al. [17] propose a mobile beacon-based positioning system to predict the location of the nodes, but it requires high energy consumption for controlling the movement of beacons. Mirza et al. [18] propose a localization scheme in which statistical model has been developed to model the sea swarm movement. It improves the prediction mechanism for the location of the nodes, but it requires complex circuit implementation, which in turn consumes a large amount of energy.

Moreover, fixed data routes are not applicable because of the multipath, doppler spread, and turbulence noise. Connection-oriented protocols such as the transmission control protocol (TCP), perform inefficiently due to this issue and are considered unsuitable for the underwater applications. Xie et al. [19] propose Segment data reliable transport protocol in which they employ tornado codes to correct the erroneous packets. The packets are transmitted in the form of blocks and a window control mechanism has been introduced to avoid the data congestion.

2.2.2. Classification of Routing protocols on the basis of localization

In UWSNs, there are mainly two broad categories of routing protocols *i.e.*, localization-based and localization-free routing protocols. This classification is based on the availability of location information for the nodes to perform the data routing. Practically, this information is hard to obtain and then update due to the continuous mobility of the nodes. In order to solve this issue for specific underwater applications, nodes are deployed at fixed locations in the water or offline localization schemes are used.

Localization-based routing protocols

In localization-based protocols [20], nodes perform data routing by using their location information. Alotta et al. [21] use the location information of nodes to propose networking between the heterogeneous underwater networks. These heterogeneous networks contain the equipment of multiple vendors. They introduce a communication stack to allow the cooperation between the multi-vendor modems and underwater vehicles. The deployed nodes use fixed path transmission to route data towards the sink node. The nodes use global positioning system to update the changes in their location. Zhou et al. [22] improve the packet delivery ratio and network reliability by using multipath communication (MPT) between the source and the destination nodes. A statistical model has been devised to identify the possible paths between the source and the destination while the optimum path is selected on the basis of the computed power consumption and packet error rate along the paths. The energy consumption over possible paths for the same packet has been calculated for the selection of an optimal path. Overall, the proposed scheme minimizes the packet error rate for the transmission.

Cario et al. [23] propose a detailed architecture of UWSN for the monitoring of water quality in artificial fish farms. Experiments have been performed to analyze the performance of the proposed architecture in terms of overall network throughput. They deployed the nodes statically by hanging them with the surface buoys. They also devise software defined communication stack in order to provide multiple network capabilities to the deployed nodes.

Localization-free routing protocols

Localization-free protocols [2] assume that nodes know only their depth information (and potentially that of their neighbors) when making routing decisions, and are mostly adopted for networks with high node mobility, channel fading etc, thanks to their capability of finding new routes for every transmission. The depth information of the deployed nodes is identified through the pressure-based sensors which are installed onboard.

These protocols perform a controlled flooding for each transmission: the way this flooding is performed distinguishes the various protocols proposed in the literature. As a consequence, the energy consumption for each transmission can be very high due to the redundancy in the packet forwardings. Nevertheless, localization-free protocols represent the most realistic choice in the implementation of routing protocols for UWSNs. In fact, they show robustness to the node movements, the variability of the fading in the underwater environment and the Doppler effect in acoustic communications. Although, these protocols consume a high amount of energy for the transmission, they seem to be more realistic and show the capability to tackle the worst conditions of the aquatic environment.

Depth-based routing protocol (DBR) [24] is one of the earliest protocols that has been introduced in the category of localization-free routing. DBR assumes that a node does not know its position but is aware of its depth thanks to the presence of sensors of pressure. The goal of DBR is that of delivering a packet harvested in any part of the network to the sinks which float at the surface of the water. To this aim, the protocol relies on some algorithms among which one is inherited from the vehicular network design, *i.e.*, the idea of holding time. Basically, every node that receives a packet to be forwarded, waits a time which is inversely proportional to the depth difference from the source node. If a node listens to a transmission of a packet that is held in the queue, then it refrains from retransmitting it. This mechanism allows the protocol to reduce the collisions, to control the flooding and to maximize the distance covered to the surface in a single hop.

Another protocol, Resilient pressure routing (RPR) [25], uses depth information, implicit acknowledgements and cryptographic mechanisms in order to provide secure data communication. The sender node uses the discovery phase to identify the presence of the receiver in its transmission range. The discovery phase is quite energy consuming as it requires a large control overhead.

Weighting depth and forwarding area division-depth based routing (WDFAD-DBR) [26] is another energy-efficient routing scheme in which authors aim to solve the void zone problem. This problem arises due to the absence of neighboring node in the transmission range of some of the deployed nodes. It results in data loss during the transmission between the source to the on-surface sink. Each forwarder node considers the depth value not only of the sender but also of its own expected forwarder in order to find its forwarding eligibility. Each node divides its possible forwarding area into primary and auxiliary forwarding regions to minimize the redundant paths towards the sink. The proposed scheme improves the energy efficiency, however, requires continuous building and updating of the neighbor tables by each node, which in turn consumes extra transmissions.

2.2.3. Oppurtunistic Routing protocols

Opportunistic routing protocols provide resilience to the deployed nodes for tough underwater conditions as they usually select a set of eligible forwarders for data forwarding. The set of forwarders is decided on the basis of different metrics, e.g., depth difference between the sender and the receiver, time of arrival of packets at the receiver and expected transmission cost (ETX) etc. The presence of more than one forwarder and the availability of multiple routes towards the on-surface sink results in an increase of overall network throughput; however, there is large energy consumption due to redundant transmissions and the hidden terminal problem. The hidden terminal problem is defined as an inability of the optimal forwarder to restrict the transmissions by the other eligible forwarders of the sender node.

Efficient routing metrics, e.g., expected packet advance (EPA) and normalized advance (NADV), are designed to solve the above-mentioned issues. Some of the recent opportunistic routing protocols [1, 27] also aim to solve the other major challenges which include local optimum problem, bottleneck issue and coverage hole problem. Energy-Efficient Cooperative Opportunistic Routing Protocol [28] proposes an improved relay based routing scheme in which fuzzy logic has been employed for the forwarder set selection. The implementation has been done in NS2 based AquaSim [29].

2.3. Other related work

Akyilidiz et al. [30] discuss the major challenges of UWSN in a detailed survey. The authors suggest the utilization of underwater vehicles and effective deployment strategies of sensor nodes as a way to tackle the issues of high end-to-end delay and coverage hole. They discuss the challenges for specific underwater applications and propose the possible solutions in the context of 2D and 3D UWSN communication architectures. Furthermore, they classify the communication schemes, according to the OSI layered model and concentrate on the design of offline localization schemes to improve the performance of these proposed communication schemes.

In [31], the authors propose a novel routing scheme; Channel Aware routing protocol (CARP) which ensures reliable communication between the hops on the basis of their packet delivery ratio to the immediate receivers. Moreover, shadow zones in the network are identified from successful previous transmission and overall network throughput is improved. In total, the scheme prefers the nodes with high probability of successful transmission in order to improve the overall network throughput, which is extremely useful for the data-aware underwater applications. Nodes use fixed data routes for transmission towards the sink and store the route information, which requires extremely complex circuits.

Xie et al. [19] propose a Segmented data transport protocol (SDRT) which mainly employs block by block packet transmission. They combine forward error correction (FEC) and automatic repeat request (ARQ) to formulate their hybrid approach and improve the channel utilization. The proposed scheme offers a replacement for the transport layer protocols designed for terrestrial networks (*i.e.*, TCP and UDP) which are not suitable for the underwater environment. During the block-by-block transmission, they implement a transmission window idea to avoid the congestion.

At a lower level, the detailed analysis of underwater channel losses with respect to the presence of multipath communication between the source and the destination node have been very useful in computing the overall delivery probability of the network. Zhou et al. [22] compute the number of possible paths between the source and the sink nodes and optimize the power consumption of the nodes involved in the shortest path. A similar type of analysis has been proposed in Link quality-aware queue-based spectral clustering Routing Protocol (LRP) [32], in which the authors devise a quality-aware cluster-based routing scheme. It improves the packet delivery ratio as the links are established between the nodes with high successful delivery probability of packets. Implementation of cluster based routing reduces the redundant transmission, but increases the computational complexity for the nodes as well as the energy consumption of the network.

Stefanov et al. [33] predict the network connectivity in a hierarchical underwater acoustic sensor network architecture. The authors attempt to improve the SNR of the network by introducing the concepts of coverage-limited and interference-limited regions. A decrease in the interference region results in an increase of the delivery probability and network throughput. In [34], the authors employed various acoustic propagation models to study the detailed performance of DBR and its improved versions. They discuss the prominent models which are used to analyze the channel losses, Doppler spread and ray tracing. These models include the Thorp model, Monterey Miami parabolic equation and Bellhop ray tracing model.

2.4. Performance evaluation of UWSN

Analysis and validation of routing protocols in underwater networks have also drawn a lot of attention in the recent years. The peculiarity of these networks requires the adjustment of the opportunistic protocols defined for vehicular networks. However, while for vehicular (terrestrial) networks, several analytical models have been proposed (see, e.g., [35]), less results are available for underwater networks. Some of the major methods to evaluate and validate the performance of communication schemes include the development of analytic models, underwater simulators, implementation of schemes using test-bed technology and real experimentation. Due to the high cost of the network deployment, less availability of experimental resources and inadequate lab equipment, analytic modeling and underwater simulators are considered as a more viable way to assess the performance of protocols. The implementation of detailed channel models and structured protocol stacks are necessary for the analysis of layer-by-layer packet flow and the performance of novel communication schemes. A lot of experimental models have been proposed to evaluate the performance at the physical layer and to compute the losses in the acoustic channel, e.g., Bellhop ray tracing model [36], Monterey Miami parabolic equation [37], and Thorp model [15]. Among these Thorp model is considered as the simplest one and it mainly considers the frequency of the signal as the deciding factor of the transmission loss.

2.4.1. Role of analytical models

Analytical models allow the researchers to understand the impact of the network parameters and protocol configurations on the system's performance in a rigorous way. Despite they usually require stricter assumptions than the corresponding simulation models, the evaluation of the performance by means of analytical model is less time consuming, since accurate simulation estimates can require high computational power.

The outcomes of analytical models are helpful in correlating the behavior of underwater communication and its performance metrics with well-established theories of the literature. The tradeoff between the performance metrics can be studied according to the targets of the designed schemes and their applications. Validation of simulators has been one of the targets of stochastic models, which is also helpful in risk assessment in case of maximum performance of the Mac and routing schemes.

To the best of our knowledge of UWSNs, there are not many analytical models to evaluate the performance of the communication schemes so there is a room for improvement in this research domain. Among the few works available, De Souze et al. [38] propose a model to analyze the energy consumption in multi-hop UWSNs. Some other works study stochastic schedulings for the data transmission policies to deal with the network latency while accounting for the energy consumption. This design is particularly related to the Mac layer as it increases the channel utilization while avoiding the packet collisions. It considers queuing delay, propagation delay and processing delay accurately to model the time of arrival of the packets. Marinakis et al. [39] formulate the channel access problem in terms of directed graphs and provide a heuristic to obtain the minimum latency. However, the acoustic absorption (as in Thorp's experimental formula) and the routing protocols are abstracted out in the computation of the transmission loss. The model is useful specifically for the time-critical applications, disaster management and seismic monitoring, etc. The model also aims to improve the channel usage by utilising SNR at the receiver node while avoiding the redundant transmissions for data acknowledgement.

Li et al. [40] develop a new routing protocol based on a Markov model which optimizes the trade-off between the packet delivery probability and the energy consumption. While the authors provide an energy-aware routing path selection, the unreliability of the links and the impact of node mobility on data transmission are ignored.

2.4.2. Role of simulators

There is a lot of on-going research in the field of protocol design for UWSNs, which includes the development of energy-efficient routing and MAC protocols. In this context the development of trusted and accurate simulators plays a pivotal role to compare new and older schemes and to cross validate analytical models. In particular, the protocol that we mainly consider in our work, DBR, represents an important benchmark for the underwater routing protocols.

Many research groups have adopted Network Simulator (NS) as a tool to assess the performance of newly designed communication schemes and as a mean to link the field experimental results on acoustic communications with simulation models and other off-field research. The Network Simulator-2 (NS2) [41] is one of the most widely used simulation tools for the development and testing of novel communication schemes. It contains the implementation of almost all major physical, MAC and upper layer protocols for both wired and wireless networks, allowing researchers to easily assess and compare the performance of novel protocols. Most of the simulators for UWSNs have been designed using the base classes of NS2. AquaSim [29] which is based on NS2, exhibits the implementation of a large number of MAC and routing protocols for UWSNs. It uses Thorp model to analyze the channel losses however, it faces memory leaks due to compatibility issues with Linux operating system. Therefore, it has been replaced by the advanced NS3 simulator, which covers the deficiencies of NS2.

Petrioli et al. [42] develop a Networking framework for underwater Simulation, Emulation and real-life Testing (SUNSET) for the implementation and validation of underwater communication schemes. SUNSET is considered as the first open source paradigm for robust simulation and emulation of acoustic communication systems due to its extensive set of libraries. However, also in this case the authors focus their attention on the lower layers of the communication protocol stack. Advanced version of this simulator contains complete protocol stack implementation for software defined networks in underwater applications. The stack have been examined by the comparison with the experimental results and have been validated, however, latest versions are not open access.

Some works (see, e.g., [33]) propose simulation designs of underwater acoustic networks (UANs). However, we must consider that the peculiarities of UWSNs do not allow one to straightforwardly apply the findings obtained for UANs to UWSNs. This model contains a Matlab implementation of the acoustic channel model and also computes the important parameters, e.g., channel impulse response, end-to-end delay, etc. It provides the capability to implement network bathymetry in order to identify realistic results for a particular underwater environment. King et al. [43] perform a critical review of five underwater network simulators and develop an event-driven simulator using OMNET++ and MiXiM network. It is developed on the basis of MiXiM modules for MAC layer. For the routing layer, they employ a simple cluster-based routing protocol along with adding the GUI-based animator for simulations.

2.4.3. Role of experimentations

Depending upon the availability of experimental resources, real-time experiments are considered as most authentic way to examine the performance of designed underwater models and architectures. It validates the performance of Mac and routing protocols also according to the application oriented designs. For example, performance of data-critical routing protocols can be evaluated in context with data-critical applications e.g., seismic monitoring or disaster prevention. Same is the case with the validation of energy-harvesting techniques which claim to harvest energy from the wave motion etc, and aim to perform efficiently for long lasting applications, e.g., oil spillage monitoring. There are some experiments done specifically to analyze the performance of proposed UWSN architectures.

Caiti et al. [8] deploy a large-scale UWSN architecture in which operations are assisted by both sensor nodes and underwater vehicles. They analyze the channel impulse response (CIR) between the communicating nodes. Apart from the presence of multipath effect, successful packet delivery paths showed higher SNR as compared to average SNR. The transmission loss and round trip time (RTT) are increased during the daylight due to the effect of sound speed profile (SSP). RTT also seemed to vary with the changes in the depth of the deployed nodes which is again caused due to SSP. During the evening time, creation of shadow zones was noticed, this resulted in the decrease in the overall network throughput. They used the Bellhop ray tracing model and confirmed the similarity index of the experimental results.

2.5. Open challenges in UWSN implementation

There are lot of challenges which the researchers face while designing new architectures for UWSNs. These can be classified according to the OSI model. Electromagnetic waves can perform sufficiently well in the fresh water but at the price of using complex circuits. Still, there is some work going on related to EM waves usages for communication in the fresh water scenarios [44]. The speed of acoustic signal varies from 1450 m/s to 1500 m/s due to change in depth of the signal, which affects the propagation delay between the communicating nodes. SSP is used to explore the opportunities to minimize the average end-to-end delay of the network according to the requirements of application-oriented designs. Ray tracing models are designed to identify the change in trajectories of the signal, which is varied due to the depth of the water. Sea bottom largely affects the trajectories, which should be analyzed to assess the realistic conditions.

Presence of shadow zones largely affects the communication during the daytime as it causes temporary loss of connectivity between the nodes and an increased bit error rate (BER). Due to long-term deployment, nodes face the issues of corrosion that affect the performance of circuits. Lot of attention is required to tackle stray current corrosion and galvanic corrosion as they quickly erode the underwater nodes and vehicles.

Most of the novel routing and Mac protocols perform efficiently, but in turn require higher complexity of the deployed nodes. This generally implies an increased energy cost, which is much higher than that required for the terrestrial sensor networks. Energy-harvesting techniques is one of the current topics of research which aims to solve the issue of high energy consumption for long-term monitoring of underwater networks. As compared to high data rate availability in terrestrial sensor networks, underwater communication faces the issue of very low bandwidth. This issue can be solved by hybrid medium techniques within the network or the Internet of thing (IoT) implementation in UWSN, which can provide services to the multiple applications using the same deployed nodes. As their systems are deployed for the long-term monitoring, it is required that nodes could be able to optimize their performance with respect to the conditions of the environment. This requires the design of optimization problems to efficiently use the network resources to perform the needed functions. Design of node deployment strategies is also one of the primary themes of current research as the nodes undergo continuous mobility, which may challenge any underwater communication scheme. This movement largely varies with the 24 hours, months and seasons. The cost for the underwater equipment is quite high due to tough condition of water, which is needed to be tackled. Most of the novel work should be done considering the large-scale network, which is realistically required for underwater applications. Network security is one of the biggest challenges due to the military purposes. Recently, the research work has been going on with respect to the denial of service attacks and fuzzy attacks, which are used to infect the network, however, these types of attacks need to be tackled using named data networking and efficient node addressing schemes.

As previously discussed, routing in UWSNs is a challenging problem not only because of the intrinsic characteristics of this class of wireless networks but also due to the performance indices that must be taken into account simultaneously such as the network throughput, the packet delivery ratio and the energy cost. For example, routing algorithms must grant a low energy cost in order to maximize the lifetime of the network's nodes. These performance indices largely depend on the configuration settings of the employed routing protocols as most of the latest routing protocols (see, e.g., [23]) are designed according to the targeted applications of UWSNs. For instance, Porto et.al [45] propose an extended form of Distance-Aware Collision Avoidance Protocol (DACAP) by augmenting it with optimized transmission power and range selection for sensor nodes. The fine control of these parameters leads to an improvement of the energy efficiency while the network connectivity is preserved. Moreover, the authors find out that the selection of the optimal transmission range in DACAP depends on the network density.

Therefore, it is crucial that the parameters of the protocol are configured to balance the various performance indices. For a given cost, the optimal configuration achieves the best trade-off between energy consumption, mean end-to-end delay, throughput, delivery probability, etc.

There are several parameters that have to be considered, including the transmission power of nodes, the configuration of routing metrics and the selection of the Mac protocol, etc., that need to be set to configure a network employing any routing protocol. Overall, the identification of the optimal network settings and configuration of routing protocols are useful in achieving best results for UWSNs. One important example, among these parameters is the identification of an optimal transmission range of the nodes. In the view of preserving the energy at the nodes, short transmissions seem to be more convenient, however, we must take into account the fact that multiple forwardings will be required. The transmission power of a node depends on the distance required to cover through a single transmission [15]. On the other hand, long distance transmissions tend to drain the battery quickly. From the point of view of the reduction of the end-to-end delay, long transmissions are clearly optimal, but this requirement must always be balanced with that of a proper policy for energy saving. The objective of this thesis is that of integrating simulation and analytical modeling to develop a framework that allows us to study the optimal configuration of a class of opportunistic routing protocols.

3

Introduction to Depth-based routing

Depth-based routing is considered as one of the most important categories for underwater routing thanks to its easiness of implementation and robustness against node's mobility. Depth-based routing uses the depth information of nodes to build a route from the source node to the on-surface sink. In general, Depth-based routing is also termed as pressure-based routing as the pressure sensors are attached to the nodes to estimate their depth. In Depth-based routing, data is forwarded from the high depth nodes to the low depth nodes. The protocols in this category aim to secure a high packet delivery ratio with a controlled network energy consumption as they prefer to select a set of eligible forwarders instead of a single forwarder for hop to hop communication.

In Depth-based routing, the position of the sink is considered on the surface of the water. In order to improve the network performance, various depth-based routing protocols propose efficient routing metrics, e.g., holding time, expected packet advance (EPA) and normalized advance (NADV), etc. In [2], the performance of several routing protocols has been compared in terms of energy consumption, end-to-end delay and network throughput. The authors have highlighted the difference in the routing approach of these protocols. They also suggest some important guidelines for the design of depth-based routing protocols. They perform an extensive survey and classify the various depth-based routing schemes on the basis of their candidate selection and candidate coordination procedures. The key benefits and deficiencies of major depth-based routing schemes have been pinpointed.

These protocols are also considered as opportunistic routing protocols as they provide an opportunity of data forwarding to the multiple receiver nodes in order to increase the network resilience against high node mobility conditions.

Most of these protocols are not completely distributed as they also get assistance from the sender node for taking the forwarding decisions, e.g., hydrocast [1] and void aware pressure routing (VAPR) [27]. Hydrocast uses the offline localization schemes while VAPR follows the approach of cluster-based communication. However, both of these protocols still forward the data from the high depth nodes to the low depth nodes.

3.1. State of the art of Depth-based routing

Among depth-based routing schemes, Depth-Based Routing protocol (DBR) [24] is considered as the pioneer routing protocol. DBR adopts a receiver based forwarding scheme in which the potential forwarders are chosen based on the depth difference between the sender and the receiver. The nodes estimate their depth by on-board pressure sensors and add this information to any packet they send out, such that all the receivers can calculate the depth difference between themselves and the transmitter.

In order to reduce redundant packet transmissions, DBR introduces the concept of a packet holding time, *i.e.*, a time that a potential forwarder waits before sending the packet. The holding time is inversely proportional to the depth difference between sender and receiver. For a given transmission range, by this mechanism, the protocol aims to cover the longest distance towards the surface at each forwarding step, as receivers further away from the surface wait longer and then drop the packet if they overhear the communication of the nodes closer to the surface.

Energy Efficient DBR (EEDBR) [46] is a more recent variation of DBR in which the residual energy of the nodes' batteries is taken into account for the selection of the forwarders as well as the difference in the depth. It is a sender based approach in which the sender node exploits the residual energy value of its lower depth neighbors to identify and then select the optimal forwarder out of a specified set of forwarders. These eligible forwarders hold the data packet for a holding time, which is computed based on their residual energy.

All the nodes store the list of their low depth neighbors as their eligible forwarders. Upon receiving the packets, the receiving node finds out their eligibility for data forwarding after checking its ID in the list sent by the sender node. The list is ordered on the basis of the residual energy values of the forwarding nodes. There is no holding time for the node which resides on the top of the list as it forwards the packet immediately, while the remaining nodes in the list compute their holding time on the basis of their position in the list. 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 (computed and broadcasted by the sink) received in the data packet. The nodes suppress the transmission, if the random number is less than the delivery ratio. Otherwise, the data packet is transmitted. In case where no data packet is overheard during the holding time, the data packet is transmitted when the holding time expires.

Figure 3.1 explains the packet forwarding criteria of EEDBR, in which both depth difference of the communicating nodes and the residual energy of the receiver are taken into account. The sender maintains the list of its low-depth neighbors and the receiver finds its eligibility for forwarding as it receives the table of eligible forwarders from the sender. In this case, node A computes the holding time of the packet based on its residual energy upon finding its ID in the forwarder list sent by node B. If it senses a low packet delivery ratio of the network, it decides the forwarding of packets based on generated random number.

Hydrocast [1] is another well-designed and energy-efficient routing protocol. It proposes a single vertical direction routing towards the surface using the depth information of the nodes. It employs offline localization at a monitoring center that uses local distance measurements (collected with sensor data) to select the subset of forwarders that maximizes the greedy progress. Note that distributed localization typically requires much iteration. The key challenges which Hydrocast tackles are the unreliability of acoustic channels and the presence of void zones in the network. A subset of neighbors of each sender node is selected as eligible forwarders to avoid the challenge of the unreliable acoustic channel. Moreover, in order to suppress the hidden terminals during opportunistic forwarding, Hydrocast proposes a simple greedy heuristic that searches for a cluster of sensor nodes with the maximum progress towards the sink. Hydrocast proposes a recovery route process to handle the local minimum issue in the network.

A local minimum occurs when neighboring nodes with a lower depth than the depth of the sender node do not exist. Due to the wave motion of water, nodes continuously change their positions which lead to the change in the neighbors for any node. There is always a chance that a forwarding node might lose its low-depth neighbors which is the cause of the local minimum problem.

Figure 3.2 [1] depicts the problem motivation of hydrocast as well as the proposed solutions. A node finds whether it is a surface or non-surface node by using dominating triangle formula and identifies the local maximum problem. Due to this problem, coverage holes are created. Using the formula of NADV and cluster formation, hydrocast computes the expected progress of packet towards the on-surface sink. Advance zones for each node are defined using the vertical cone shape of the cluster. It is also useful for solving the

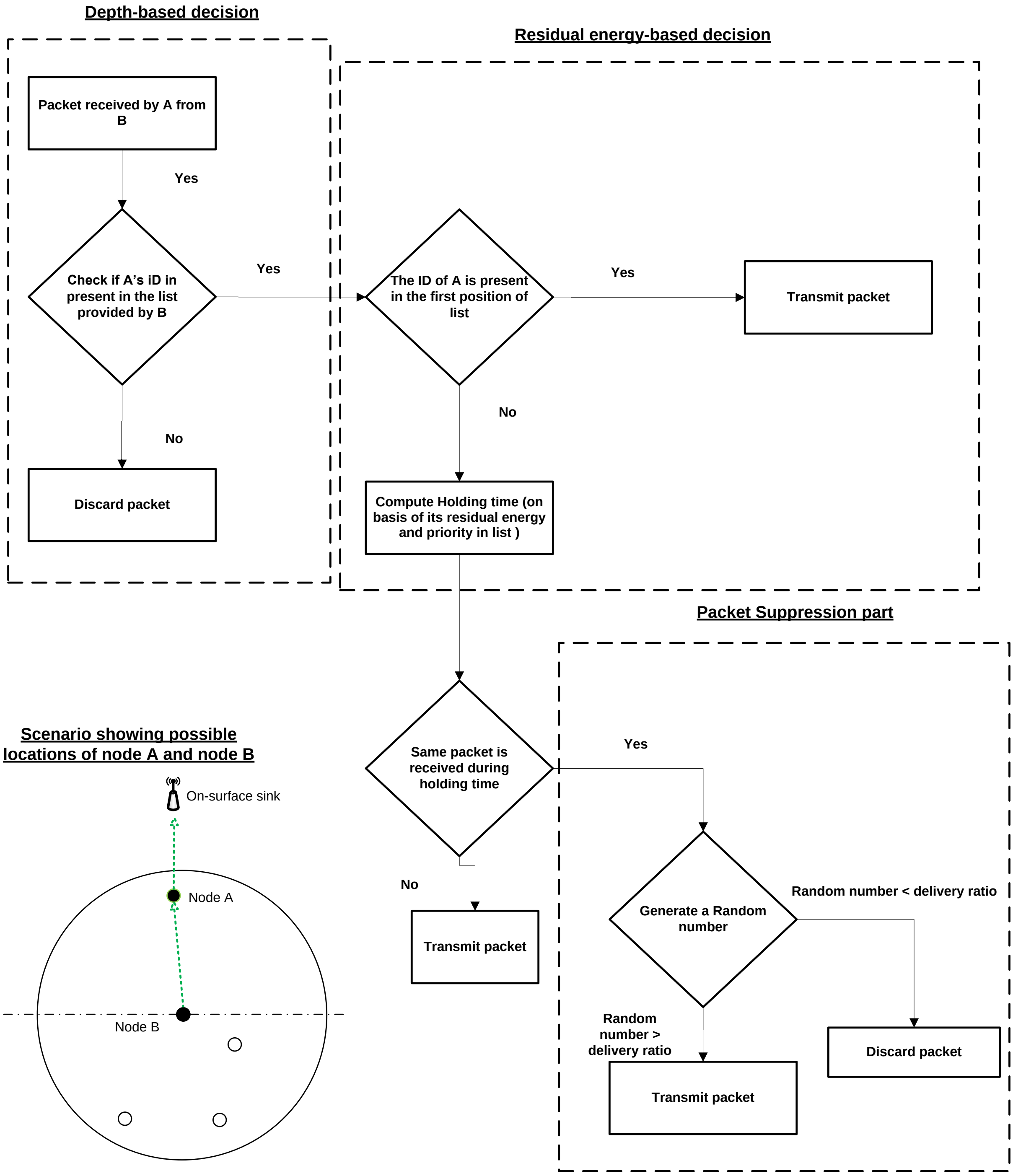

Figure 3.1.: Methodology of EEDBR

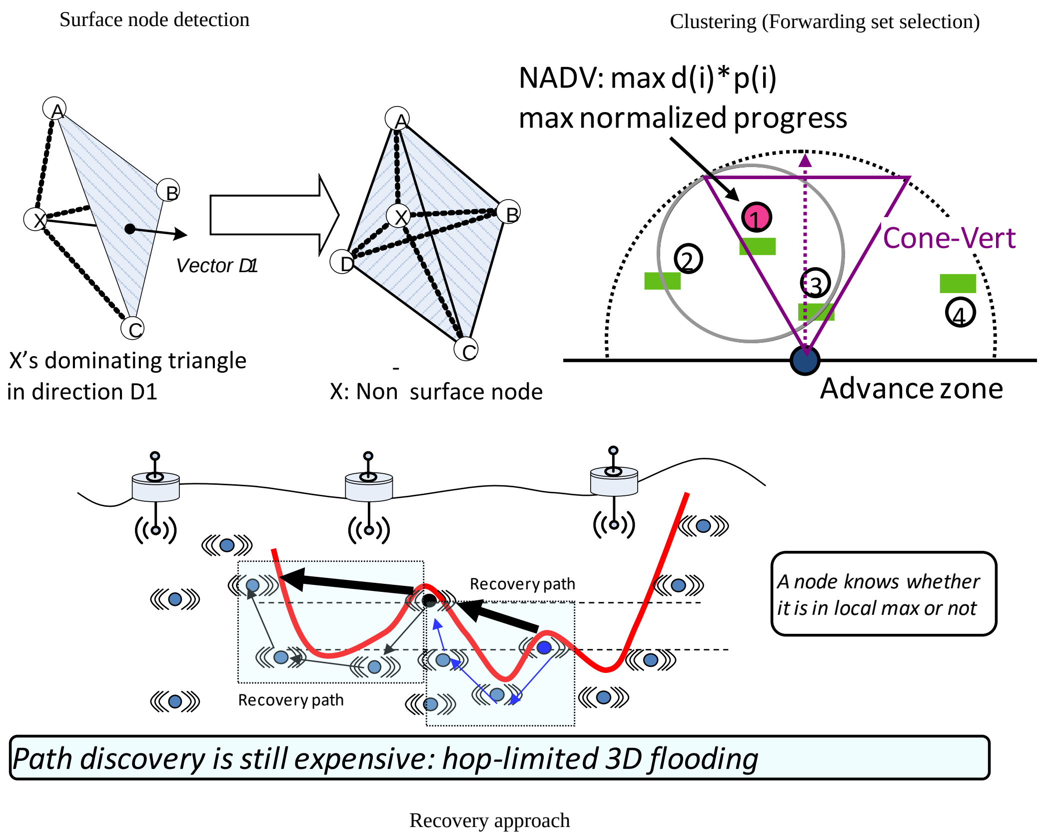

Figure 3.2.: Methodology of Hydrocast (taken from [1])

Table 3.1.: Comparison of routing protocols based on their characteristics

Protocol	Forwarding decision	Candidate set selection	Candidate coordination
DBR	Single entity	Receiver-side based	Timer based
EEDBR	Single entity	Sender-side based	Timer based
Hydrocast	Clustered	Hybrid approach	Control packet based
VAPR	Clustered	Hybrid approach	Control packet based
GEDAR	Clustered	Hybrid approach	Control packet based
WDFAD-DBR	Clustered	Hybrid approach	Timer based

hidden terminal problem. It employs a recovery path by identifying the surface nodes and their local maximum problem.

Weighting depth and forwarding area division-dbr routing protocol (WDFAD-DBR) [26] minimize the presence of coverage holes during data forwarding by taking into account the depth information of the neighboring hops. Forwarding area division improves the delivery ratio however, it requires large network overhead for neighbor prediction. In [47], the authors propose Geographic and Opportunistic Routing protocol (GEDAR), which introduces the idea of automatic topology control in case of presence of a void hole in UWSNs. Nodes control their depth to move towards the void hole, although this movement may result in high energy consumption.

3.1.1. Evolution of depth-based routing into opportunistic routing

Opportunistic routing protocols have been evolved from the depth-based routing as they also aim to forward packets towards the low depth nodes from the high depth nodes. Unlike the earlier depth-based routing protocols, opportunistic routing protocols e.g., [1] and [27], use offline localization. Although they are successful in increasing the network throughput and minimising the energy consumption still their implementation seems little bit unrealistic due to continuous node mobility. In contrast to these novel opportunistic approaches (see, e.g., [1] and [26]), DBR is a completely distributed routing protocol as it exhibits the capacity to tackle worst underwater conditions.

As previously discussed in section 2.2.3, Opportunistic routing protocols for UWSNs are classified as receiver-based and sender-based [2]. For receiver-based algorithms, a node that receives a packet decides if it is going to be a forwarder based on some factors among which the depth difference between itself and the sender usually plays the major role (other factors may be the residual energy in a battery). Sender-based algorithms, on the other hand, are more difficult to implement and require the sender node to specify which neighbor node(s) will be the forwarder(s).

3.2. Why DBR?

Although there are multiple opportunistic protocols designed in the last decade, however, DBR [24] is still considered as the most applicable routing scheme due to its completely distributed nature and simplicity of implementation. DBR is an opportunistic routing protocol for UWSNs which provides good performance both under high and low node mobility scenarios. Unlike many of its enhancements, DBR acts as a perfect receiver-based routing protocol, which makes it suitable for error-prone underwater conditions. It does not depend on offline localization schemes which are hard to implement in the varying underwater environments.

DBR shows a major difference from its later version e.g., EEDBR, VAPR and Hydrocast. The main drawback of EEDBR is that the implementation of the sender-based forwarding scheme is much more complicated than that of DBR and requires then nodes to maintain routing information and neighbour tables.

DBR is a receiver-based forwarding and the receiver decides whether to forward data or not, on the contrary, in EEDBR, the sender selects the set of eligible forwarders and also takes part in their holding time computation through giving them their sorted list according to their residual energy values. In DBR, receiver use the concept of depth threshold and compute holding time on the basis of depth difference with the sender, however, in EEDBR, receiver compute holding time on the basis of their residual energy and the priority value which is again given by sender to it and computed on the basis of receiver's residual energy information. Moreover, VAPR, WDFAD-DBR and hydrocast use offline localization schemes which make them more complex and tough to implement.

3.3. The DBR routing protocol

The goal of the DBR protocol is to transmit a packet containing data harvested by an arbitrary underwater node to the sink floating on the surface. In DBR, nodes use omnidirectional acoustic transmissions and it is assumed that nodes are aware of their depth. In practice, this is possible thanks to sensors capable of measuring the pressure at a node. Once a node performs a transmission, it encodes its own depth in the packet and only the neighbour nodes with a lower depth than the sender are eligible for forwarding that packet. In order to control the packet flooding, DBR uses two mechanisms: the first is the introduction of a *depth threshold*, *i.e.*, all the nodes whose depth difference with the sender is lower than this threshold cannot forward the packet. This is aimed to void retransmissions by nodes which are too close to the sender. The second mechanism consists in the introduction of a *holding time*. Intuitively, the holding time is the delay that a node has to wait before forwarding a received packet: short delays imply a higher probability of being the forwarder.

3.3.1. Methodology of DBR

During the packet forwarding, each transmitting node modifies the depth value of the packet with its own value. In order to handle the high node mobility and the dynamic conditions of underwater channel, the routes are not permanent. Therefore, each packet contains: the **(i)** Node ID of the forwarder **(ii)** Depth of the forwarder **(iii)** Packet sequence number, **(iv)** Node ID of the source node.

Figure 3.3 explains the algorithm employed by DBR. As the node receives the packet, it checks its sequence number for the previous transmission. Upon finding its forwarding for eligibility, node checks for depth threshold and then computes the holding time of the packet, which ultimately decides the scheduled sending time of the packet. If the node receives the same packet that is in the sending queue, it reschedules the sending time of the packet.

The optimal configuration of DBR depends on a set of parameters among which a pivotal importance is played by the choice of the transmission power, the holding time and the depth threshold. Specifically, the transmission power determines the distance over which the packet can be received correctly, which in turn affects the number of hops needed to reach the sink, the overall energy consumption, the packet delivery probability and the end-to-end delay. In general, there is a trade-off between long and short distance transmissions, *i.e.*, too many hops to the destination lead to high end-to-end delays while too few require a high transmission power that consumes the nodes' batteries too fast.

Example 1. *Consider the scenario shown in Figure 3.4. A is the transmitting node, and the circle denotes its transmission area. The packet is received by all the nodes in the transmission range with the exception of E whose reception is disturbed by noise. The eligible forwarders are the set of nodes whose depth is lower than the depth threshold (dashed line in the picture),* i.e., *nodes C, E and F. Hence nodes C and F compete for the retransmission according to a "race policy" on their holding times: the one with the shortest delay will be the forwarder. B and D are the non-eligible forwarders so they discard the packet of A.*

Other important features of DBR are as follows [24].

Multiple paths of data forwarding: DBR uses priority queues for storing the packets which are sorted according to their scheduled sending time.

Avoiding the retransmission of the same packet: DBR uses a packet history buffer of fixed length in which the packet sequence number and source ID of the packets which have already been transmitted are stored. If the receiver finds the copy of an already transmitted or discarded packet, it discards the packet.

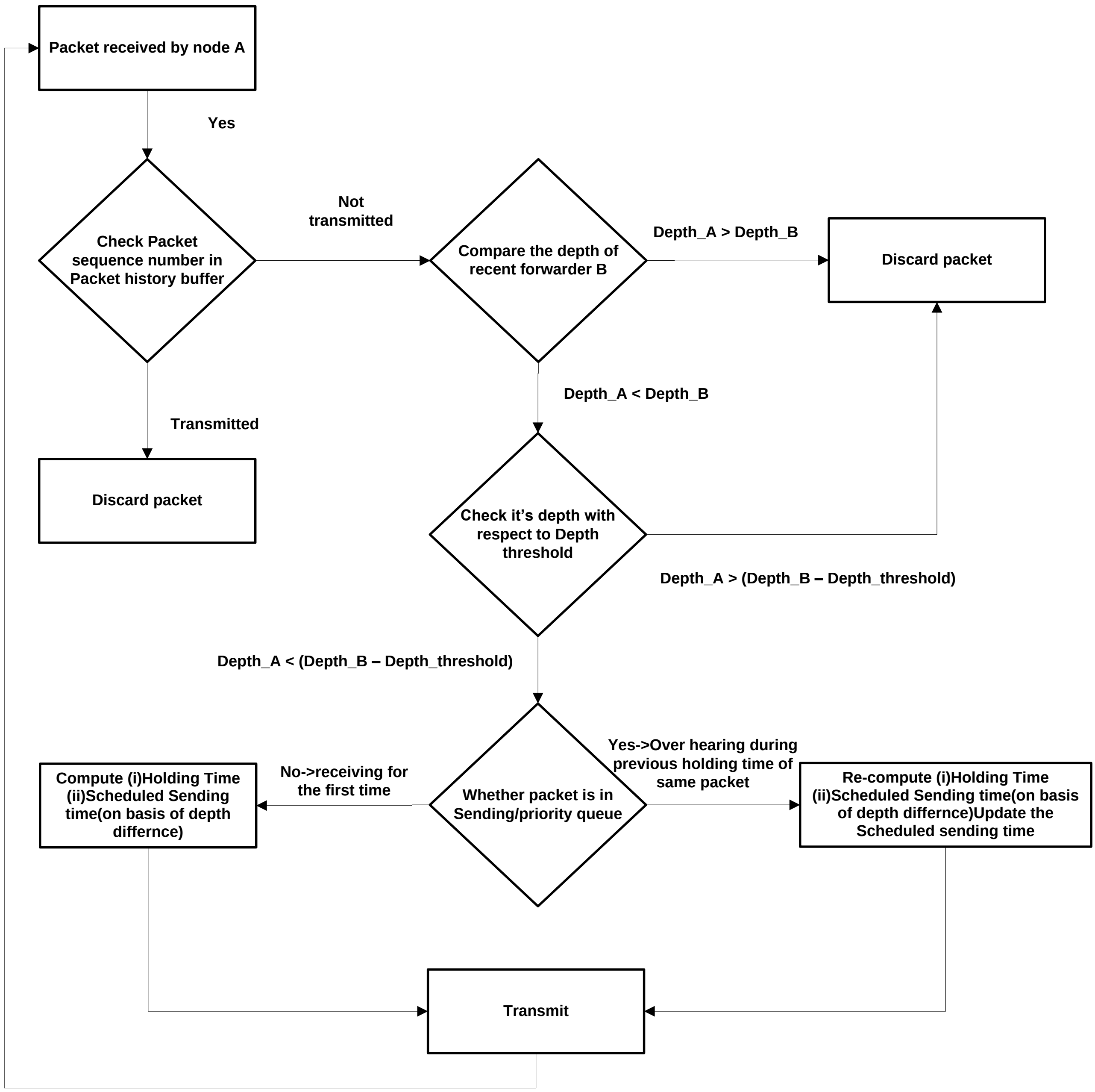

Figure 3.3.: Methodology of DBR

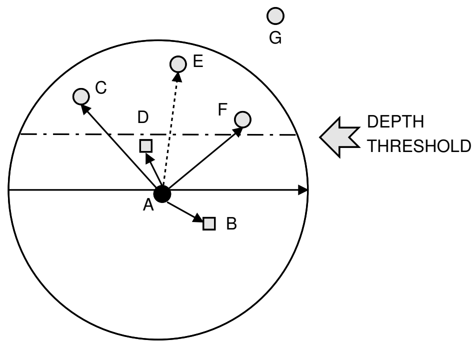

Figure 3.4.: Scenario considered in Example 1

Reducing the number of interferences: In its original formulation, in order to reduce the number of hops along the forwarding path, DBR aims at selecting the forwarding node with the minimal depth. In its basic definition, the holding time is computed in such a way that the node with the maximum depth difference with the sender has the minimum holding time. Redundant transmissions may arise, if the neighbour with a maximum depth difference fails to suppress the transmission of other eligible forwarders due to the long propagation delay among them. In order to reduce this undesired behaviour, the holding times are scaled by a factor δ which ensures that they always are long enough to encompass the intermediate propagation delay.

In DBR, we identify three operational modes of sensor nodes [48]: (i) Transmission mode: nodes only transmit the enqueued packets and ignore any other received packet while this mode is active; (ii) Receiving mode: Nodes receive the packets and the modem remains turned on; (iii) Idle mode: The acoustic modem is turned off while the node waits for the expiration of the holding times for the packets already stored in the buffer.

3.3.2. Computations of the holding time in DBR

In the original formulation of DBR, the only state variable used to compute the holding time is the depth difference between the sender and receiver. According to [24] the holding time depends on the depth difference d between the nodes as:

$$f_{\mathrm{DBR}}(d) = \left(\frac{2\tau}{\delta}\right) * (T - d) \tag{3.1}$$

where T is the maximal transmission range of a node, τ is the maximum propagation delay of one hop, *i.e.*, $\tau = T/v_0$ (where v_0 is the sound propagation speed in the water) and δ is a scaling factor of the holding time, which is chosen in order to achieve the optimal performance of the network and to minimise the hidden terminal problem. There is a trade off in the proper choice of δ. In fact, small values of δ lead to higher holding time values which reduce the network energy consumption, but, on the other hand, increases the packet delay and worsen the throughput. Conversely, higher values of δ reduce the holding times, but redundant transmissions occur with a higher probability and hence we observe a higher energy consumption.

3.3.3. Computations of the holding time in EEDBR

In EEDBR, nodes compute the holding time on the basis of their residual energy instead of depth difference. This is also one of the major differences between DBR and EEDBR while other differences include implementation of the sender based routing and low depth neighbor tables. These differences make the performance of EEDBR more dependent on the network conditions, e.g., node mobility scenarios. Nodes IDs should be included in the sender node, otherwise they cannot act as an eligible forwarder in EEDBR. The holding time in EEDBR is computed as follows:

$$f_{\text{EEDBR}} = \left(1 - \frac{current\_energy}{initial\_energy}\right) * max\_holding\_time + p \tag{3.2}$$

where $max\_holding\_time$ denotes the maximum time for which a node can hold a packet. It is a system parameter. p is the priority value and acts as a scaling factor among the nodes having same residual energy.

3.4. Concluding remarks

This chapter highlights the importance of DBR among the opportunistic routing protocols. DBR exhibits the ability to tackle the high node mobility scenario with minimum control overhead. As compared to EEDBR, Hydrocast, VAPR and many later opportunistic protocols, DBR entirely is a complete receiver-based forwarding scheme. It maintains a high packet delivery ratio by introducing the time scaling factor during the computation of holding time. This holding time duration defines the scheduled sending time for any received packet and eventually the selection of low-depth forwarder of the sender node. We also discussed the methodologies of EEDBR and Hydrocast in detail and identify their deficiencies while facing tough underwater conditions.

Part II.

A new simulator for UWSNs

4

Design of a simulator: AquaSim-Next Generation for UWSNs

In the last decade, UWSNs have been widely studied because of their peculiar aspects that distinguish them from terrestrial WSNs. Among these aspects of UWSNs, we just emphasise that the acoustic transmission is much slower with respect to the terrestrial wireless communication and nodes are susceptible to frequent unpredictable movements due to the wave motion. The applications of UWSNs range from environmental monitoring to military defense. Routing protocols in UWSNs propose various methods for data routing from the nodes to the base stations. The definition of efficient routing protocols in UWSNs is a challenging topic of research because of the intrinsic characteristics of these networks, such as the need of handling the node mobility and the difficulty in balancing the energy consumed by the nodes.

Simulators for underwater networks play a major role in validating the performance of previous schemes as well as for the preliminary evaluation of the novel communication schemes. These simulators are usually designed in multiple scripting languages, e.g. C, C++, Matlab, Python and Java, etc. Due to the cost of the underwater equipment, it is almost impossible to analyze the performance of novel communication schemes through experimentation. Therefore, the design of simulators for underwater communication has been one of the main topics of research in the recent years. The implementation of complete layered model in the simulators is useful in analysing the sequence of packet flow during node-to-node communication.

The main contribution of this chapter is presenting a novel simulator for studying DBR protocol and its variants as well as novel routing protocols. Our simulator is based on AquaSim-Next Generation (NG) [3] which is a specialized tool for studying underwater networks. With our work, we improve the state of the art of underwater routing protocol simulators by implementing, among other features, a detailed cross-layer communication and an accurate model of the operational modes of acoustic modem and their energy consumption. The simulator is open source and freely downloadable [49].

Structure of the chapter The chapter is structured as follows. Section 4.1 discusses the state of the art on network simulators designed for underwater networks. It also provides some relevant details of their implementations, some information about their libraries and their animation capabilities. Section 4.2 explains the details of our contribution in this proposed work. Section 4.3 gives a detailed description of the data forwarding mechanism used by DBR and how it is implemented in the event-based simulator. Section 4.4 discusses the validation of our simulator and the impact of the configuration parameters of DBR on the performance indices by means of simulations. Section 4.5 concludes the chapter. The work described in this chapter has been published in [50].

4.1. Previous work on underwater simulators

In the literature, we find a wide set of simulators developed for UWSNs. Although some of them are based on the framework provided by Network Simulator-3 (NS3) such as [51], some others are stand-alone tools developed in some general purpose programming languages [52].

Climent et al. [51] propose the NS3 based simulator for their multiple sink architecture of UWSNs. The purpose of the simulator is to analyze their proposed energy-efficient adaptive hierarchical and robust architecture (EDETA). The simulator also examines the fault-tolerant mechanism of the protocol and validates its performance. EDETA implements base class of underwater acoustic network (UAN) model previously designed for NS3, which computes the transmission loss of the acoustic signal and delivery probability of the packets. However, the simulator lacks a capacity to support the novel opportunistic routing protocols.

Maseiro et al. [52] design a detailed underwater architecture in their tool, namely Design, simulate, emulate and realize test-beds for underwater network protocols (DESERT). DESERT is a multi-tasking tool as it exhibits the capability to emulate the network by using its C and C++ based libraries. It has been designed by using the base classes of NS-Miracle [53] which is an improved version of NS. Like other NS-based simulators, some of the libraries have been implemented in tool command language (TCL) and OTCL. The authors concentrate on the static routing protocols for the multihop communication and network layer design. They also validate the performance estimated by the simulator by using their test-bed technology.

In [54], the authors devise a 3D simulator and animator for underwater environment using the applications of the Fast Light Toolkit (FLTK). It also includes OpenGL for the 3D rendering and animation. However, they consider only low-level protocols, and hence ignore the evaluation of the routing schemes. The main purpose of the simulator is to increase the capability of NS2 by designing a 3D Network animator (NAM). FLTK is useful for its GUI widgets which display the mobility of nodes according to the implemented mobility models.

Guerra et al. [55] devise another NS2-based simulator for underwater networks, called World Ocean Simulation System (WOSS), specifically designed for studying the physical and MAC layer protocols. They also employ ray tracing models to define the limitations on transmitted signal amplitude during acoustic propagation. The authors validate the performance of the simulator by comparing the results with experimental data obtained from underwater communication networks at Pianosa Island. Apart from the acoustic channel models, Aloha, T-lohi MAC and distance aware collision avoidance protocol (DACAP) have been tested for analysing the performance of MAC layer designs. Performance evaluation of various implemented schemes has been performed considering both Poisson and event-driven generated traffic.

In [15], for the first time, the authors introduce the model of the acoustic channel in NS2 to explain the physical layer communication at nodes in underwater networks and also compare the results with the analytical models designed in Matlab. The base class of the simulator implements the energy consumption model by using the Thorp's model and the passive sonar equation. Energy consumption for various distances between the communicating nodes have been calculated by assuming the 30 dB SNR threshold at the receiver node. Later simulators of underwater communication mostly follow the above-mentioned model due to its accurate performance.

Borowski et al. [56] examine the acoustic channel and its transmission loss to deal with the tribulations in the acoustic propagation and provides a model to compute the channel loss. They adopt a measured impulse approach, noise and transmission loss data in order to simulate the channel in a more realistic manner. In contrast to our work, they focus on the analysis of the Bit-Error-Rate (BER) in a shallow time-invariant channel rather than on the evaluation of the performance of the routing algorithms.

AquaSim [29] provides simulation models of physical, MAC and few routing protocols designed for UWSNs. However, AquaSim rely on the heterogeneous architecture of NS2 and implements an object-oriented programming style based on four different scripting languages. As a consequence, the implementation of new simulation models and their efficiency can be somehow cumbersome. AquaSim also exhibits the potential to demonstrate the deployed nodes in 2D scenario by using its Network animator (NAM). Some of the later simulators which have been derived from AquaSim propose 3D animation, hence enhancing quality of GUI interfaces for opportunistic routing in UWSN.

In [3], the authors propose a new framework for the simulation of UWSNs, AquaSim-NG, based NS3 [57] and its libraries. With respect to NS2, NS3 shows several essential improvements but on the other hand it suffers of a still limited amount of developed libraries. The whole structure of AquaSim-NG has been encoded into a unique language, C++, and a more efficient memory management has been achieved. This, together with other optimisations which have been implemented, makes AquaSim-NG a more efficient and easy-to-use simulation framework for UWSNs with respect to AquaSim. AquaSim-NG has a large number of ported libraries from its previous version, moreover, it has improved embedded features related to security, real-time simulation, and information-centric integration.

The works that are closely related to the one presented here are [24, 46] where the authors implement DBR and EEDBR, respectively, in NS2. With respect to these works, our simulator exploits the inter-layer communication that is implemented in AquaSim-NG developed for NS3 but that was not present in the libraries for NS2 [3]. Inter-layer communication is an important feature to consider in order to obtain accurate estimates of the performance indices of DBR. Another improvement with respect to the versions presented in [24] is that our simulator takes into account the computation of the operational mode durations of sensor nodes and hence can provide an accurate estimate of packet loss, end-to-end packet delay and battery duration.

4.2. Contributions

In this section we emphasize the contributions of our work.

1. We develop an open source simulator [49] for DBR protocol and its variants in AquaSim-NG which allows the research community to obtain accurate estimates of the performance indices for depth-based routing architectures. One of the characteristics of DBR is that its definition requires cross-layer communications and hence we have devoted particular attention to the implementation of accurate models also for the physical, MAC and the network layer together with their interdependencies. The simulator has been implemented in C and C++ languages. It covers some major deficiencies of AquaSim [29] that include poor memory management, bounded real-time module support and steep user learning curve.

2. Our model is validated with an accurate implementation of a low-level simulator developed in Matlab that takes into account aspects that are abstracted out from the previous DBR implementation of AquaSim-NG. Specifically, the Matlab simulator is based on the recent work by Parastoo et al. [58] where a detailed statistical model of underwater channels is given. The experiments show the robustness of the proposed DBR implementation. A lot of similarity was found among the close approximations of the performance indices while comparing the two simulators. It is mainly due to implementation of range-based propagation and specialized noise generators in our model. These features are useful for computing the localized packet interference which is effective in predicting the packet delivery probability.

3. The implementation based on NS3 and AquaSim-NG, compared to the previous ones, provides more simplicity of use and an improved memory management thanks to the automatic de-allocation of objects. From the model implementation prospective, we consider packet header allocation and a realistic handling of packet queues. The busy terminal problem support provides accuracy in performance evaluation considering the computation of energy consumption.

4. Finally, we observe that our simulator is faster and scales better with the number of nodes than the previous ones [24] available in the literature. We show also a deep analysis of the impact of DBR configuration parameters on the UWSN performance based on simulation experiments carried out with the tool that we propose. Synchronization between the operational modes of the acoustic modem and the upper layer protocol configuration results in precise calculation of results.

4.3. Design of the simulator

In this section we describe the simulator that we propose for DBR. We give a description which introduces the implementation choice layer by layer. In practice, we have performed a refactoring of the classes *AquaSimPhyCmn* (Physical Layer), *AquaSimMac* (MAC Layer) and *AquaSimRouting* (Routing Layer) which will be described in details in the following three sub-sections.

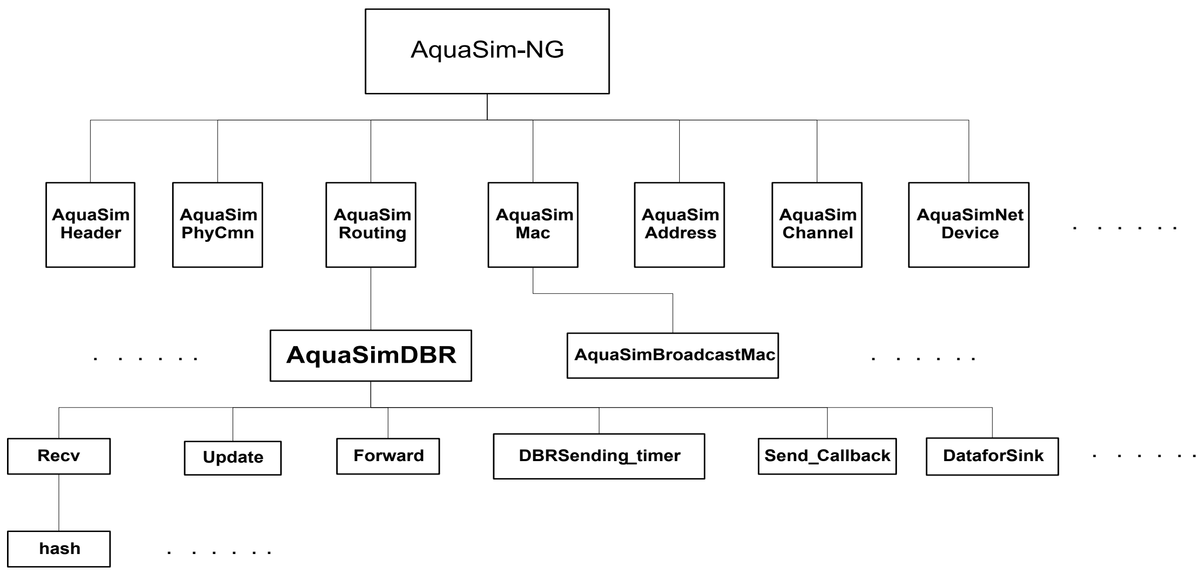

Figure 4.1.: Architecture of AquaSim-NG

4.3.1. The physical layer

Models for the propagation of acoustic waves aim at mathematically representing the quality of the transmitted signal as a function of several factors, such as the external noise and the distance between the source and the destination. Therefore, it is possible to compute the packet delivery probability in an underwater channel given some parameters as the absorption and the attenuation effects of the water. These effects largely vary with the node's depth, wave motion and temperature of water (see, e.g., [59]).

Packet delivery probability estimation One pivotal element of our model is function $f(x)$, *i.e.*, the probability that a packet is correctly received by a node placed at a distance x from the sender. We use one of the most common models for the acoustic channel, *i.e.*, the Urick's model [58, 60]. According to this model the path loss over a distance d for a signal of frequency ν is given by the following formula:

$$A(d,\nu) = d^k a(\nu)^d , \tag{4.1}$$

where $a(\nu)$ is the absorption coefficient and k is the spreading factor.

The spreading factor k takes into account the geometry of the signal propagation. Informally, we can think that k is used to model different characteristics of the antennas: for instance, in general, an omnidirectional antenna will have a lower value of k than the one associated with a directional antenna.

For spherical spreading it is usually assumed that $k = 2$ (see, among others, [1]). $a(\nu)$ is obtained by using Thorp's formula [60].

The average SNR $\Gamma(d)$ at a distance d from the source node is given by:

$$\Gamma(d) = \frac{E_b/A(d,\nu)}{N_0} ,$$

where $A(d,\nu)$ is computed by Formula (4.1), E_b is the average transmission energy per bit, and N_0 is the noise power density.

Coherently with most of the literature on acoustic communication, we adopt $dbrepa$ as the unit for the total path loss (see, e.g., [15]).

We consider a small-scale Rayleigh fading effect modelled as in [58] where the probability of error for each bit is independent and computed as:

$$p_e(d) = \int_0^\infty p_e(x) p_d(x) dx , \tag{4.2}$$

where:

$$p_d(x) = \frac{1}{\Gamma(d)} e^{-x/\Gamma(d)} .$$

We assume the binary shift keying modulation which is widely used in modern acoustic modems. In [61] the expression for $p_e(d)$ is given as:

$$p_e(d) = \frac{1}{2}\left(1 - \sqrt{\frac{\Gamma(d)}{1+\Gamma(d)}}\right) .$$

Since we assume packets of size m bits and independent errors, the probability that a node correctly receives a packet at distance d from the source is:

$$f(d) = (1 - p_e(d))^m . \tag{4.3}$$

In order to change the operational modes [48] of the nodes, we access their states through the base class $AquaSimNetDevice$. This is also used to set the network parameters of nodes, e.g., its location and its network address. Moreover, the state of the modem is controlled by the functions in the classes of $AquaSimPhyCmn$.

Acoustic modem goes from idle to receiving mode when it detects the incoming wake up tone (which is sent by the transmitting nodes before the beginning of the packet transmission), and remains in this mode until the end of the receiving of packet. Afterwards, the mode is switched to idle again. Then, the node remains in idle mode, if the sending queue is empty while if the expiration of a holding time for enqueued packet occurs, it moves to the transmission mode. During this mode, the node transmits all the enqueued packets with expired holding time before going back into idle mode.

4.3.2. The MAC layer

Our implementation of the MAC layer relies on the class $BroadcastMac$ which is based on the previously developed Broadcast MAC protocol [62] available on AquaSim-NG which is itself derived from the base class of $UnderwaterMac$. The interface with the routing layer is handled by function $Recv$ that we implemented in order to allow compatibility with DBR. $BroadcastMac$ is the natural choice for simulating controlled flooding based protocols as DBR. Its behaviour is rather simple: when a node has a packet to send, it simply broadcasts the packet after sensing the channel as idle, otherwise it backs-off. We set the maximum number of back-off times after which the packet is discarded. The model implements a best-effort delivery mechanism without acknowledgements. Congestion is handled by $BackoffHandler$ function.

The class of $AquaSimBroadcastMac$ controls the settings of the modem and has the capability to quickly change the status of net device by employing the functions of $PowerOn()$ and $PowerOff()$. This plays a pivotal role in the estimation of the network energy consumption.

4.3.3. The network layer

The details of the DBR routing protocol has been discussed in section 3.3.

The implementation of the network layer is done in class $AquaSimDBR$ that represents the core of our DBR simulator and incorporates the functions needed for interfacing with the lower layer, *i.e.*, the Broadcast MAC protocol.

The main features of DBR are implemented in three functions:

- *Recv* implements the reception of a packet from the MAC layer and performs the operations described by Algorithm 1. Specifically, this function computes the holding times and performs the operation of inserting or purging packets from the priority queue upon the arrival of a new packet or a copy of one already stored, respectively. In our implementation, we allow for flexibility in specifying the holding time in order to be able to compare different routing policies that may take into account several state variables like the depth and the residual energy of the nodes. The holding time function can be specified by a separate file in order to make the parameterisation of the simulation easier. The parameters in the user-defined holding time function are set through a C++ script by accessing the state variables through $AquasimNetDevice$ (e.g., for knowing the depth of the node) or by using the class of $AquaSimHeader$ for what concerns the information on the packets (e.g., the depth of the sender).

- *Forward* performs the operations required to forward a packet once its holding time expires.

- *Update* is used to manage the priority sending queue according to the computation of the holding times.

Packet headers are handled by the library class $AquaSimHeader$ which takes into account the peculiarities of UWSN communication as coherently implemented by $AquaSimAddress$.

We now present more details of Algorithm 1. Received packets are firstly checked through a $hash$ pointer function in order to avoid redundant transmissions (line 14). The

Algorithm 1: Processing of received packets in sending queue at routing layer

```
hashPtr ← stored sequence number of already discarded or transmitted packets
GetPosition().z ← depth value of current node
packet−>GetUid() ← sequence id of packet
queue.purge(packet) ← checks whether packet is in sending queue
depth ← stored depth value of sender
queue ← queue of scheduled packets for sending
latest_time ← gives the packet with most recent
Queue_Item ←
gives the packet stored in sending queue with its scheduled sending time and sequence id
scheduled sending time
holding_time ← computed holding time for current packet

if ((hashPtr != NULL)) then
    if ((model->GetPosition().z) > depth) then
        if queue.purge(packet) then
            packet=0;
            return false;
        end if
    else { (model->GetPosition().z) < depth }
        double scheduled_send_time = Simulator::Now().ToDouble(Time::S) +
        holding_time;
        int pck_id = packet->GetUid();
        if (queue.purgenow(packet, scheduled_send_time)) then
            if (queue.empty()) then
                Queue_Item *q = new Queue_Item(packet, scheduled_send_time, pck_id);
                queue.insert(q);
                latest_time = scheduled_send_time;
                Send_Timer->Schedule(Seconds(holding_time));
                return true;
            else { (queue.update(packet, scheduled_send_time, pck_id)) }
                Queue_Item *q = new Queue_Item(packet, scheduled_send_time, pck_id);
                queue.insert(q);
                latest_time = scheduled_send_time;
                Send_Timer->Schedule(Seconds(holding_time));
                return true;
            end if
        else
            packet=0;
            return false;
        end if
    end if
end if
```

hash pointer function increases the network efficiency by discarding previously transmitted or discarded packets, and it stores the sequence ID's of packets up to a specified number. We see that the received packet is considered for forwarding only if the depth specified in the header is more than the current depth of the node (test at line 20). Otherwise, it is used to purge the enqueued packets with same sequence ID (lines 16-19). The scheduled sending time for accepted packets is computed by taking into account the holding time provided as input to the function. Then, these packets are stored in order according to their holding times in the sending queue (lines $24 - 36$). If the sending queue has already a copy of a packet with the same ID, the algorithm maintains a single copy of that packet and the scheduled sending time is set to the one with the earliest expiring time. The nodes have a finite capacity buffer and the received packets exceeding the buffer capacity are discarded. However, due to high propagation delay of acoustic channel, the buffer of nodes is capable of storing all the received packets at any specific moment.

The cross-layer communication needed to control the operational modes of the modems is implemented by ***Send_Callback*** function in class of ***AquaSimDBR***. Finally, the model passes the control data to the application layer at the sink and the source node by using ***DataForSink***. Figure 4.1 illustrates the architecture of the main class of ***AquaSimDBR*** and its subclasses.

Remark 1. *In contrast with the previous models of DBR implemented in NS2, in our implementation, we are able to study the so called busy terminal problem [63]. This issue of DBR is caused by the fact that the computation of the holding times based only on the depth differences tends to choose a small set of routes with very high probability. As a consequence, some nodes are much more stressed by the network traffic than others and as the density of the network increases, they begin to drop packets, thus causing a reduction of the packet delivery ratio metric. This is a key-problem of DBR and the importance of a simulator capable of reproducing this phenomenon is witnessed by the recent literature on the topic (see, e.g., [63]).*

4.4. Validation of the simulator and Simulation experiments

In order to validate our simulator, we compare the estimates that we obtain by using our DBR implementation on AquaSim-NG (using the depth-based strategy for the computation of the holding times) and the estimates previously obtained with the DBR implementation on Aquasim. Notice that the comparison is meaningful for UWSNs whose parameters are set in such a way that the busy terminal problem is negligible. In fact, as discussed in Section 4.3, we provide a more detailed model for the network layer that allows us to compute the effect of the interferences due to the busy terminal in more accurate way. In all our experiments, in such cases, we have a difference between our estimates and those derived in [24] below 7%.

A second set of experiments has been carried out to validate our implementation of the physical layer. The complexity of the physics of underwater transmission makes the implementation of the physical layer challenging and prone to errors. In order to avoid these problems, following the procedure of [58], we have compared the estimates of the AquaSim-NG implementation with that of a Matlab model.

Parameter	Value
Network size	250m ×250m ×250m
Deployment	Random uniform
Initial energy of nodes	50J
Packet size	64 Bytes
Transmission Range	75m
Node mobility speed	1 m/s, 3 m/s
Transmission power consumption	2 W
Receiving power consumption	0.1 W
Idle power consumption	1 mW
Mobility pattern	Random walk
f	$3kHz$

Table 4.1.: Simulation Parameters

As a consequence of this more accurate modelling, we can study the impact of the busy terminal problem and the nodes' operational modes on the network performance obtaining new insights on the behaviour of UWSNs. Previous works do not consider these features and obtain different estimates for networks with high node density.

4.4.1. Simulated scenarios and methodology

In the simulations, we compare different scenarios for DBR with various depth thresholds and holding time computation mechanisms. Network nodes are deployed randomly with uniform spatial distribution, the sink is placed on the surface of the water and the source node is placed at the highest depth and at a random position with all the other nodes moving with the speed of 1m/s or 3m/s, according to the experiment. The source node transmits one packet after every 2 seconds with a packet size of 64 bytes. Other details of the simulation settings are present in table 4.1. Notice that these settings are coherent with those proposed in [24].

All the estimates shown in the following subsections are based on 15 independent experiments and we build the 95% confidence intervals. The interval widths have been always below 5% of the expected index measured in during the simulation.

4.4.2. Impact of the configuration parameters on the performance of DBR

In this section we study how the value chosen for parameter δ affects the performance of the network. Intuitively, shorter values for δ reduce the probability of interferences but increase the end-to-end delay of the network, whereas larger values lead to an energy waste due to the high probability of packet corruption caused by the interferences.

Figure 4.2 shows the end-to-end delay in networks with various node densities and different choices for the δ parameters. For $\delta = R/4$ we observe an end-to-end delay which is approximately 12% higher than that observed for $\delta = R$. Moreover, we observe that the end-to-end delay decreases as the network becomes more dense because of the decreased accumulated propagation delay between the source and the destination. Figure 4.3 points out the trade off between the network speed and its energy consumption which increases

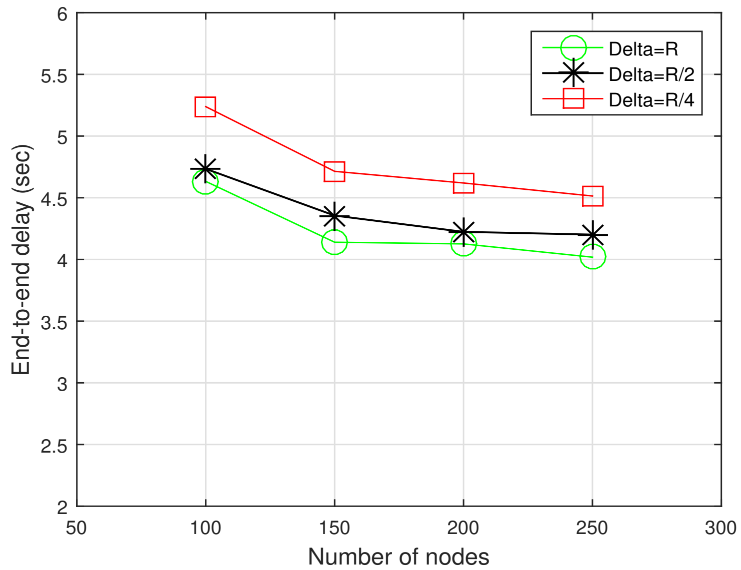

Figure 4.2.: Average end-to-end delay of packets with various value of δ in DBR (sec)

with the values chosen for δ. The higher energy consumption is due to the increased number of transmissions in the network and hence the nodes spend a longer time in the transmission mode which is highly energy consuming. Consulting figure 4.3, it is clear that as the number of deployed nodes increases, the total energy consumption increases but the observations hold true for all the considered values of δ.

Remark 2. *It is worth to emphasise that the trade off between energy consumption and end-to-end delay has been accurately studied for the first time in this paper thanks to the detailed simulator that has been developed which takes into account the working modes of the network nodes and their energy consumption.*

4.4.3. Cross validation with physical layer model in Matlab

The main purpose of this section is to validate our simulator with a physical layer statistical model implemented in Matlab based on the results shown in [58]. We consider the packet delivery ratio and the total energy consumption and performance indices. Figure 4.4 shows the comparison between the estimates obtained by the simulator of DBR and those obtained by using the statistical model of [58]. We can see that the trends shown by the simulations are very close with a higher difference in sparse networks. This is due to the fact that our model consider the duration of operational modes of the nodes and the dropping of packets due to the busy terminal problem. Clearly, these issues are more evident in sparse networks. Figure 4.5 shows the energy consumption estimated by the two simulation models. In this case we observe a higher discrepancy between the two models (between 20%) although the trend is maintained. This is due to the fact that the Matlab model does not take into account of the different energy consumption of the different operational modes and of the protocol inter-layer communication characteristics. Therefore, in Matlab, the simulation model is capable of efficiently investigating the performance metrics at physical layer thanks to a precise channel model, but is unable to incorporate important MAC and routing layer characteristics such as an accurate handling of packet queues and idle channel detection.

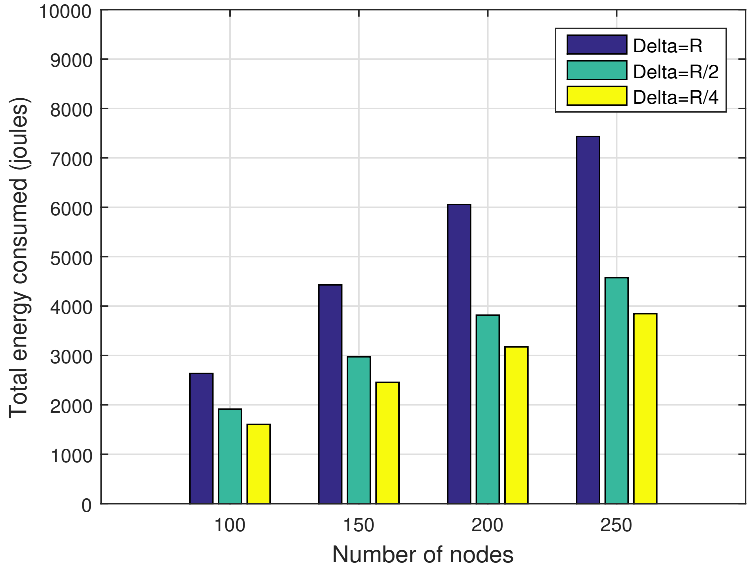

Figure 4.3.: Total energy consumption of network with various value of δ in DBR (joules)

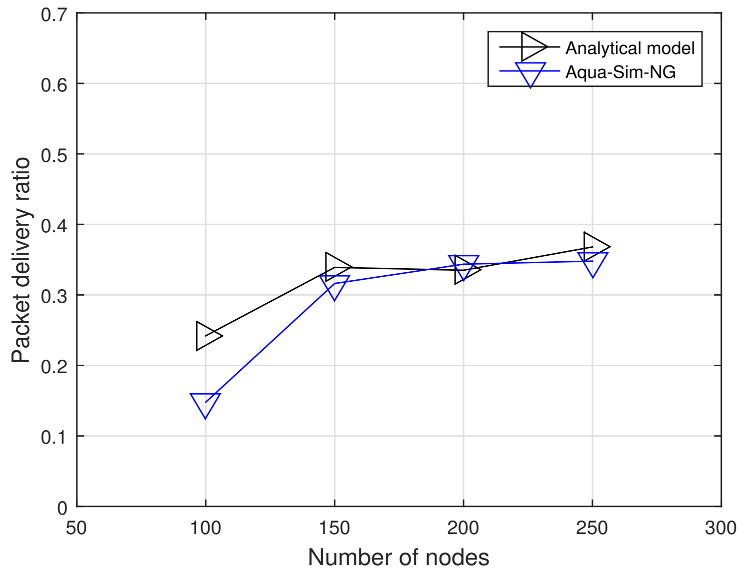

Figure 4.4.: Analysis of the packet delivery ratio between the models for DBR

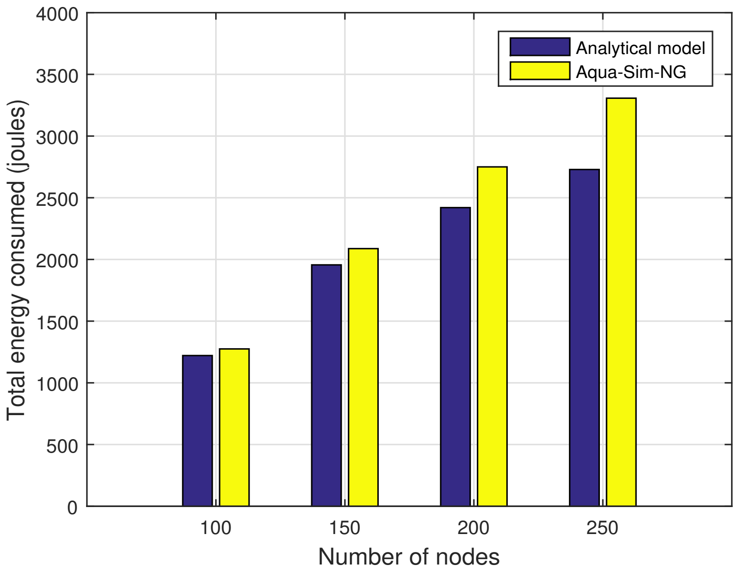

Figure 4.5.: Analysis of the total energy consumption between the models for DBR (joules)

4.5. Concluding remarks

In this work, we have presented a new simulator based on AquaSim-NG for depth-based routing protocols. With respect to previous works, our simulation model is more efficient thanks to the design characteristics of AquaSim-NG and NS3. Moreover, we consider two aspects that have been previously abstracted out and that we show to be important to accurately assess the system performance, *i.e.*, the accurate computation of the energy consumption associated with different operational modes and the inter-layer communication features required by DBR based schemes.

Therefore, the main strengths of our simulator are an implementation of the layered architecture of DBR, the use of AquaSim-NG libraries and the support of 3D networks with mobility. The proposed tool is then used to study the optimal configuration parameters of DBR. With respect to previous results, our findings expose the problems of low delivery ratio and high end-to-end delay for certain working scenarios of DBR. These observations were previously ignored due to the more abstract implementation of the protocol stack.

The tool is available with its complete libraries at [49].

Part III.

Analysis and Optimisations in Depth-based routing

5

Stochastic Modeling of Depth-based Routing in Underwater Sensor Networks

Interest in UWSNs based on acoustic communication has rapidly grown over the last decade. In this field, the design of energy-efficient communication protocols is a crucial task as battery replacement may be unfeasible in practical scenarios. While routing protocols play a pivotal role in determining the efficiency of UWSNs, only a few studies investigate analytical stochastic models for their quantitative analysis and optimization. In the work proposed in this chapter, we consider the routing protocol DBR [24], and define a stochastic model that allows us to numerically derive important performance indices, like the end-to-end delay, the energy consumption and the packet delivery probability, in terms of the configuration parameters. The model accounts for peculiar factors of UWSNs, including the impact of node deployment and mobility, and the high transmission loss of the acoustic channel. We present insights that are useful in setting DBR configuration parameters to optimize the trade-off between delivery probability, energy consumption and end-to-end delay.

5.1. Introduction

As mentioned in the previous chapters, over the last two decades, underwater applications like seabed management, sea-mine detection, environmental monitoring, etc. have motivated the adoption of UWSNs as a communication infrastructure. As a consequence, many research effort has been devoted to study their performance and derive guidelines for their design. In contrast to most terrestrial wireless networks, UWSNs widely adopt acoustic communication as its intrinsic properties like low signal interference and large transmission coverage make it suitable for the underwater environment. Like their terrestrial counterparts, UWSNs adopt multi-hop routing protocols that aim at delivering the harvested data packets to on-surface sink nodes. The design of these routing protocols must account for the energy consumption of the network — battery replacement is considered unfeasible or prohibitively expensive — as well as for common performance indices like the expected end-to-end delay, the packet delivery probability and the network throughput.

Among routing protocols for UWSNs, an important role is played by localization-free protocols [2]. While such protocols provide a high network resilience, this may come at the expense of considerable energy consumption caused by redundant packet transmissions and the hidden terminal problem. In this work, we study this trade-off by proposing and analysing a stochastic model for DBR. In particular, we propose a numerically tractable stochastic model that can accurately capture the dynamics of DBR. For this model, we show that one can efficiently calculate the main performance metrics including the mean end-to-end delay, the delivery probability and the expected energy consumption. In comparison to simulation, these performance measures can be calculated much faster, which in turn allows for speeding up the optimization procedure to find the optimal configuration of the UWSN. With respect to previous work that addresses the problem of assessing DBR performance, this is the first analytical model taking into account node deployment and mobility, as well as the intrinsic properties of acoustic transmissions including the path loss and the bit error rate. The model is validated by comparing its results with the estimates obtained by resorting to stochastic simulations.

Structure of the chapter The remainder of this chapter is structured as follows. In Section 5.2 and 5.3, we relate the contribution of the present chapter to the literature by discussing related work and introducing the motivation for the model at hand, respectively. Section 5.4 then presents the stochastic model and the numerical algorithm to efficiently calculate the key performance measures of the model. In Section 5.5, we illustrate our approach by some numerical examples before drawing conclusions in Section 5.6.

5.2. Related work

In this section, we discuss some research work that are related to the findings that we describe in this chapter. In the last decade, the performance analysis of UWSNs and their optimization and control have drawn the attention of many researchers. However, most of the authors rely on network simulations rather than analytical models. In general, while simulation models are very accurate, obtaining the performance indices is very time consuming and their adoption for optimization purposes can be very expensive. Among the analytical models, Guan et al. [64] examine the spatial and temporal uncertainty of the underwater acoustic channel and develop a statistical model that is used to propose a novel distributed MAC scheme with an optimized transmission strategy. Pignieri et al. [65] propose an analytic model for channels in underwater networks. In these papers, neither the computation of the mean end-to-end delay and energy consumption nor the impact of the routing protocols on the networks performance is considered.

UWSNs are different in many aspects from their terrestrial counterparts. For example, energy consumption is higher due to longer distances that need to be crossed and due to complex signal processing. Since the communication speed is equal to the speed of sound, the propagation delay is also much higher than the speed in the terrestrial networks. Routing is a crucial part of any network, and hence most of the recent works in UWSNs have focused on developing the efficient routing algorithms. Ayaz et al. [13] provide a detailed survey on routing protocols used in UWSNs and classify them according to their functionality. Since node mobility largely impacts the performance of UWSNs, many location-based routing schemes [17, 66] have been developed which keep full dimensional location information. In contrast, DBR only needs depth information of the nodes that can be obtained easily and with a small amount of energy thanks to pressure sensors. For this reason, DBR is widely used and is often the basis of most of routing and MAC forwarding schemes [67].

In UWSNs, note that full localization schemes which compute the Euclidean distance between all neighboring nodes consume considerable energy as the devices need to obtain the required information about the positions of these nodes. Hence, these algorithms are difficult to implement in practice. Yu et al. [26] propose a Weighting Depth and Forwarding Area Division DBR routing protocol which accounts for the depth difference of two hops: not only the depth difference of the current hop but also the depth difference of the next expected hop. It achieves an improved packet delivery ratio as it tackles the issue of coverage holes during transmission towards the sink. More recent work from Rehman et al. [28] proposes an energy efficient cooperative opportunistic routing protocol which improves the network lifetime by applying fuzzy logic for relay node selection towards the network sink. Chao et al. [68] minimize the expected number of transmissions for successful delivery of a packet to the sink. Few other works [69, 70, 71] exploit extra capabilities of a node, e.g., the ability to move autonomously in order to minimize the energy consumption in the deployed sensor network.

5.3. Problem Motivation and contribution

In this work, we consider the DBR scheme and analyze its performance through a stochastic model. In contrast with the previous works in the literature, we provide an algorithm to efficiently calculate various performance indices, including the distribution of the number of hops it takes to send from the bottom of the network to a surface node, the level dependent energy consumption and the mean end-to-end delay. As the model accounts for the impact of node deployment and the high transmission loss of the acoustic channel, it can be used to understand the behaviour of DBR at the network level.

Although many stochastic models have been proposed and analyzed to study the characteristics of underwater channels, only few results are available for studying and optimising routing protocols of UWSNs. We aim to fill this gap by devising a probabilistic model to assess the performance of DBR. Analytic models of UWSNs are important tools that provide insight into the dynamic behavior of the communication schemes at the physical, the MAC as well as at higher network layers. The model proposed here finds practical applications in designing a UWSN equipped with DBR. It can support the roll-out of such a UWSN by finding the optimal configuration parameters without resorting to time-expensive simulation studies. Therefore, we can summarize our contribution as follows:

- We propose a two-dimensional probabilistic model of DBR which captures its key characteristics, including transmission delays, the acoustic channel, node mobility and holding times based on depth differences.
- We show that the key performance indices can be calculated quickly. We devise computation schemes to calculate the hop-distribution, the delivery probability, the level-dependent energy consumption and the end-to-end delay.
- By means of a numerical example, we discuss how the network performance depends on environmental characteristics like the node density and the overall transmission loss, thereby showing that the model at hand can support the design of UWSNs.

5.4. DBR and its Stochastic Model

We briefly recall present DBR and introduce a stochastic model to assess its performance.

5.4.1. Summary of Depth-based routing

Although, we have already discussed the detailed architecture of DBR in Section 3.3 however, we provide here a brief description with the aim of keeping the chapter self-contained as much as possible. DBR [24] is a packet forwarding protocol for UWSNs which uses depth information to relay information from underwater sensors to data sinks at the surface. In DBR, every node has a pressure sensor which enables the node to estimate its depth while the nodes are in general unaware of their exact 3D position.

The key determinant which decides which node will forward the information is the depth difference between the sender and the receiving node. More precisely, when a node transmits a packet, it includes its own depth information in the header. Among the (possible multiple) nodes that correctly receive the packet, the forwarder is decided

Table 5.1.: List of Notations used in the model

Notation	Definition
U	Total number of deployed nodes in the network
L	Total number of depth levels in the network for a node
Δ_d	Total depth of the network
Δ_w	Total width of the network
M	Number of horizontal positions on a particular level for a node
S	Position of the source node at the bottom level of the network
T	Position of the sink node at the top level of the network
(i, j)	Location of a node with position j at level i in the network
b_j	Probability that the node occupies position j at a particular level in the network
$d_{ij}^{i'j'}$	Euclidean distance between nodes at locations (i, j) and (i', j')
T_r	Transmission Range of a node
N^{ij}	Set of nodes within the transmission range of node at (i, j)
$p_m(d)$	Probability that the packet is successfully delivered over distance d
$P_{ij}^{i'j'}$	Acceptance probability of a packet from location (i, j) to (i', j')
$h_k(i, j)$	Probability that packet is accepted at (i, j) in k-hops
$D_P(i, j; i', j')$	Propagation delay when the packet is sent from (i, j) to (i', j')
$D_H(i, j; i', j')$	Holding time when the packet is sent from (i, j) to (i', j')
w_{ij}^k	Mean delay of k-hop communication to reach (i, j)
$c_{ij}^k(i', j')$	Mean energy consumption at position (i', j') from (i, j) in k-hop communication

according to two mechanisms. First, a *depth threshold* is installed. This is the minimum depth difference that allows a receiver node to become an eligible forwarder. Secondly, with the aim of maximising the distance covered by one hop, a depth-difference dependent *holding time* is introduced. That is, every packet to be forwarded is kept at the receiver node for a time interval which decreases linearly with the depth difference between the sender (as indicated in the packet header) and itself. In this way, nodes closer to the surface have shorter holding times and actually forward the packet if they correctly receive the packet. Once a node overhears a re-transmission of a packet that is stored in its *priority queue*, it removes this packet and cancels its holding time in order to prevent redundant transmissions.

The holding time D_H for a certain depth difference d can be expressed as follows [24]:

$$D_H(d) = \left(\frac{2\tau}{\delta}\right)(T_r - d), \tag{5.1}$$

where T_r is the maximal transmission range of a node, τ is the maximum propagation delay of one hop, i.e., $\tau = T_r/v_0$ (where v_0 is the sound propagation speed in water) and δ is a scaling factor which is chosen in order to achieve optimal performance of the network and to minimize the hidden terminal problem. We choose $\delta = T_r/4$ in the remainder in accordance with literature [24].

5.4.2. Node location model

For the sake of readability, we present a model for DBR in a two-dimensional environment. The extension to 3 dimensions is straightforward.

We consider an UWSN with U nodes. The target or sink node is located at the surface level whereas the source node is located at the bottom. While assuming fixed positions for source and sink, we allow for movement of the nodes that relay the information. In

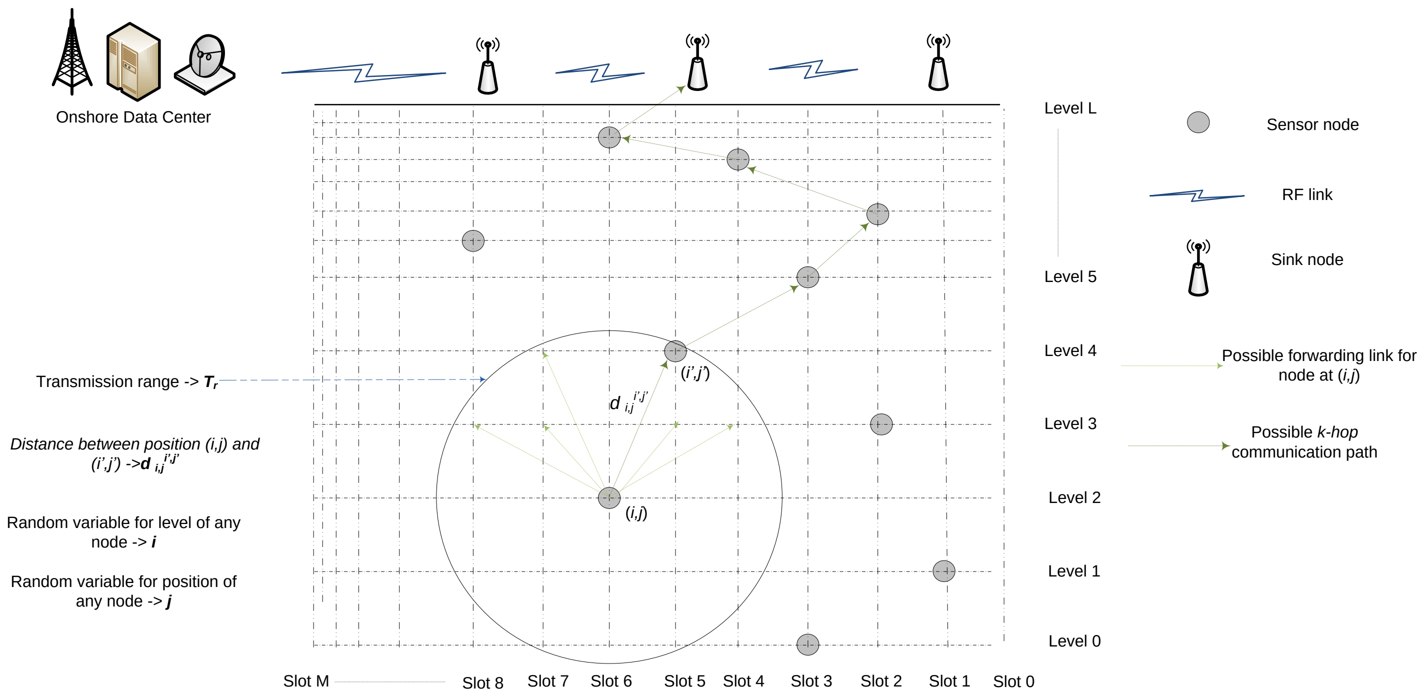

Figure 5.1.: Design of the Probabilistic model for DBR

particular, we divide the total depth difference Δ_D between source and sink into $L + 1$ depth levels, level 0 being the level of the source and level L being the level of the sink. One sensor node is present at each depth level which randomly moves in the horizontal direction. Figure 5.1 demonstrates the design of the Probabilistic model for DBR.

The nodes can move, but remain at a fixed depth level. To simplify the analysis, we divide the range Δ_W in which the nodes move horizontally into M slots with the same length, and assume that the node is always located at one of the $M + 1$ slot boundaries (which we label from 0 to M). The position of the node at each level is assumed to be an independent random variable. Let b_j denote the probability that the node is in position j. We here assume that the distribution of the horizontal position of the node is independent of the level ($j \in \{0, 1, \ldots, M\}$). For ease of reference, we enlist the major notations of the model in table 5.1.

5.4.3. Delivery probability of a node

We consider the underwater acoustic channel that is described in [72]. The path loss $A(d, f)$ of the acoustic channel over a Euclidean distance d for a signal having frequency f can be expressed as:

$$A(d, f) = d^s a(f)^d \,.$$

Here, the spreading factor s describes the geometry of the propagation; spreading factor $s = 2$ corresponds to spherical spreading and $s = 1$ to cylindrical spreading. The absorption coefficient $a(f)$ depends on the frequency and is expressed in dB/km using Thorp's experimental formula, see [60].

We can then express the average Signal-to-Noise ratio over the distance d in terms of the path loss:

$$\Gamma(d) = \frac{e_b}{N_0\, A(d, f)} = \frac{e_b}{N_0\, d^s\, a(f)^d} \,.$$

Here, e_b is the average transmission energy per bit and N_0 is the noise power density of the additive white Gaussian noise channel. We assume the binary phase shift keying modulation technique which is widely used in acoustic modems [73]. In accordance with [27], the bit error probability over distance d can be expressed as:

$$q_e(d) = \frac{1}{2}\left(1 - \sqrt{\frac{\Gamma(d)}{1+\Gamma(d)}}\right).$$

For a data packet with m bits, the probability that the packet is successfully delivered over a distance d therefore equals:

$$p_m(d) = (1 - q_e(d))^m .$$

For ease of notation, we introduce a notation for the Euclidean distance between nodes. Let $d_{ij}^{i'j'}$ represent the distance between nodes (i, j) and (i', j'),

$$d_{ij}^{i'j'} = \sqrt{\left(\frac{\Delta_D}{L}\right)^2 (i-i')^2 + \left(\frac{\Delta_W}{M}\right)^2 (j-j')^2}\,.$$

In addition, let $N^{ij} = \{(i', j') : d_{ij}^{i'j'} \leq T_r\}$ be the set of nodes within transmission range of node (i, j).

In DBR, a packet is accepted by a node at position (i', j') if (i) node (i', j') is in the transmission range of the sender node (i, j), (ii) node (i', j') successfully receives the packet and (iii) all the nodes located in N^{ij} that are above (i', j') do not accept the packet. Let $P_{ij}^{i'j'}$ denote the probability that a data packet is successfully received at (i', j') when sent from (i, j), we then have,

$$P_{ij}^{i'j'} = b_{j'}\, p_m\left(d_{ij}^{i'j'}\right) \prod_{\ell=i'+1}^{L} (1 - Q(\ell; i, j)),$$

for $(i', j') \in N^{ij}$ and where $Q(\ell; i, j)$ is the probability that the packet is successfully delivered at level l,

$$Q(\ell; i, j) = \sum_{k=0}^{M} b_k\, p_m\left(d_{ij}^{\ell k}\right) 1_{\{(\ell,k)\in N^{ij}\}}\,.$$

Here $1_{\{\cdot\}}$ denotes the indicator function which equals 1 if its argument is true, and 0 if its argument is false. In other words, the sum above only includes nodes within the transmission range of the node at position (i, j).

5.4.4. Analysis of k-hop communication

We now focus on the of number of hops needed for the data to be successfully delivered from source to sink. We first calculate the probability that any node in the network accepts the data packet from the source in one hop. Clearly nodes situated at an immediate upper level of the source will have zero probability to receive the data in one or more hops, as only direct communication is possible. Let S be the position of the source at the bottom level and T be the position of the sink at the surface level of the network. Let

$h_k(i,j)$ represent the probability that the data is accepted at (i,j) in k hops. The one-hop probability can be written as:

$$h_1(i,j) = \sum_{i'=1}^{i-1} \sum_{j'=1}^{M} P_{i'j'}^{ij} P_{0S}^{i'j'} .$$

Note that the terms in the sum are only non-zero for $(i',j') \in N^{0S} \cup N^{ij}$. Moreover, we here assume that the position of the nodes (at the different levels) can be modeled by an independent random variable for every transmission.

Similarly, the delivery probability in two hops can be written as:

$$h_2(i,j) = \sum_{i'=1}^{i-1} \sum_{j'=1}^{M} P_{i'j'}^{ij} h_1(i',j'),$$

while the delivery probability of k hop communication can be written by induction as:

$$h_k(i,j) = \sum_{i'=1}^{i-1} \sum_{j'=1}^{M} P_{i'j'}^{ij} h_{k-1}(i',j') . \tag{5.2}$$

Given the values $h_k(i,j)$, we can now easily express the delivery probability at the sink. Indeed, the packet reaches the sink if it is delivered in any number of hops,

$$\bar{h} = \sum_{k=0}^{L} h_k(L,T) .$$

5.4.5. Computation of the mean end-to-end delay

The propagation speed of the acoustic signal in the water is $v_0 = 1500\,m/s$ which is much lower than that of terrestrial radio-frequency based signals. Thus, the propagation delay is significant in UWSN and can have a considerable impact on the performance of the system. Apart from the propagation delay, we also need to account for the effect of holding times which depend on the depth difference between sending and receiving nodes. Let $D_P(i,j;i',j')$ and $D_H(i,j;i',j')$ denote the propagation and holding time delays when the packet is sent from (i,j) to (i',j'), then:

$$D_P(i,j;i',j') = \frac{d_{ij}^{i'j'}}{v_0} , \tag{5.3}$$

and:

$$D_H(i,j;i',j') = \frac{2\tau}{\delta}\left(T_r - \frac{\Delta_D}{L}(i'-i)\right) , \tag{5.4}$$

for $i' > i$ and $(i',j') \neq (L,T)$. Furthermore, $D_H(i,j;L,T) = 0$, as there is no holding time at the sink.

In order to find the mean delay, each possible path of the network needs to be explored. To this end, let $W_{i,j}$ denote the waiting time for a packet to reach (i,j) and let $H_{i,j}$ denote the number of hops it takes. We now calculate the mean delays w_{ij}^k, given that it takes k hops to reach (i,j),

$$w_{ij}^k = \mathsf{E}\left[W_{i,j} 1_{\{H_{i,j}=k\}}\right] .$$

We again use a recursive scheme, similar to that for the delay calculations, for calculating the acceptance probability for the data packets in k hops. To start, we find for one hop communication,

$$w_{ij}^{1} = \sum_{i'=1}^{i-1}\sum_{j'=0}^{M}\Big(D_H(0,S;i',j') + D_P(0,S;i',j') + D_H(i',j';i,j) + D_P(i,j;i',j')\Big)\,P_{0S}^{i'j'}\,P_{i'j'}^{ij},$$

To calculate w_{ij}^{k} for $k > 1$, we condition on the position of the last hop. That is, to reach (i, j) in k hops, we need to reach some (i', j') in $k - 1$ hops, and then reach (i, j) by direct communication. The waiting time is then the sum of the waiting time to reach (i', j') and the transmission and holding times to reach (i, j) from (i', j'),

$$w_{ij}^{k} \;=\; \sum_{i'=1}^{i-1}\sum_{j'=0}^{M}\Big(w_{i'j'}^{k-1} \;+\; D_H(i',j';i,j)h_{k-1}(i',j') \;+\; D_P(i',j';i,j)h_{k-1}(i',j')\Big)P_{i'j'}^{ij}\,. \tag{5.5}$$

Finally, we can calculate the mean end-to-end waiting time, conditional on the packet reaching the sink, by summing over the number of hops that it takes to reach (L, T), and by dividing by the probability that the packet reaches the sink,

$$\bar{W} = \frac{1}{\bar{h}}\sum_{k=0}^{L} w_{LT}^{k}\,.$$

5.4.6. Energy consumption

In order to study the expected energy consumption in the network, we recursively calculate the energy consumption for all node positions in the network to transmit to a particular node in a fixed number of hops. More precisely, let $C_{ij}(i', j')$ denote the energy consumption in position (i', j') for transmitting from the source to node (i, j) and let $H_{i.j}$ denote the number of hops to transmit to node (i, j) as before, we then study the mean energy consumption given the number of hops,

$$c_{ij}^{k}(i',j') = \mathsf{E}\left[C_{ij}(i',j')1_{\{H_{i,j}=k\}}\right]\,.$$

Note that $c_{ij}^{k}(i', j') = 0$ for $i \le i'$ since nodes above (i, j) cannot forward to (i, j).

To start with one hop communication, we have

$$c_{ij}^{1}(i',j') = \gamma\,P_{i'j'}^{ij}\,P_{0S}^{i'j'}\,.$$

Here γ denotes the amount of energy a single transmission takes. That is, $C_{ij}(i', j') = \gamma$ if the single forwarding hop is in position (i', j') and $C_{ij}(i', j') = 0$ if this is not the case.

We further calculate the values $c_{ij}^{k}(i', j')$ for $k > 0$ recursively. There is energy consumption at position (i', j') if it is reached in $k - 1$ hops, followed by direct communication, or if (i', j') is part of a $(k - 1)$-hop path to some intermediate node (above level i'), from which (i, j) is reached. We have:

$$c_{ij}^{k}(i',j') = \gamma\,h_k(i',j')\,P_{i'j'}^{ij} + \sum_{\ell=i'+1}^{i-1}\sum_{m=0}^{M} c_{\ell m}^{k-1}(i',j')\,P_{\ell m}^{ij}\,. \tag{5.6}$$

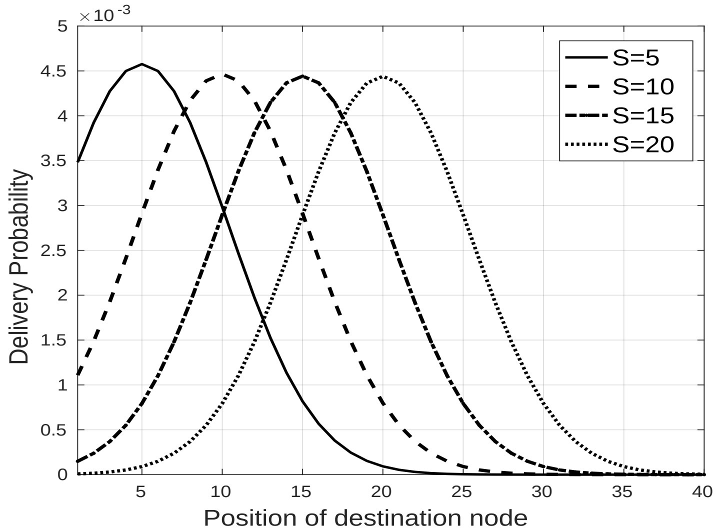

Figure 5.2.: Delivery probability for direct transmission from source to sink for different positions of the destination

We can finally calculate the energy consumption at each level in the network, by summing over the number of hops to reach the destination, and by summing over the different positions at the same level,

$$c(i) = \sum_{k=0}^{L} \sum_{m=0}^{M} c_{LT}^{k}(i, m) \, .$$

5.5. Numerical Results

In this section, we numerically study different performance measures of the model at hand. We assume that the total depth of the network is $\Delta_D = 500$m with $L = 50$ depth levels. Note that there is only one sensor node at each depth level meaning there are 50 nodes in the network. We keep the values of the numerical parameters in line with the values in [24]: we set $s = 2$, $v_0 = 1500\,\mathrm{m/s}$, $\delta = T_r/4$ and $\tau = T_r/v_0$. Finally, we assume data packets of 50 bytes. These parameter values are used in all plots.

5.5.1. Delivery probabilities

We first investigate the delivery probabilities for direct communication. We assume that each node can move horizontally to $M = 50$ locations over a range of $\Delta_W = 500$m, each position being equally likely. We further choose the transmission energy such that $e_b/N_0 = 57$dB, and assume that the transmission range is only bounded by transmission errors ($T_r = \infty$). Fig. 5.2 shows the delivery probability by a direct transmission from the source to a node at level 10 vs. the position of this node for different source positions S as indicated. The shortest distance between source and sink is obtained if both are aligned, which also leads to the maximal delivery probability.

Fig. 5.3 shows the same delivery probability, but we now fix the position of the destination node at 10 and vary its depth level. Again, different source positions S are assumed as indicated. There is an outspoken optimal depth level: at first the delivery probability

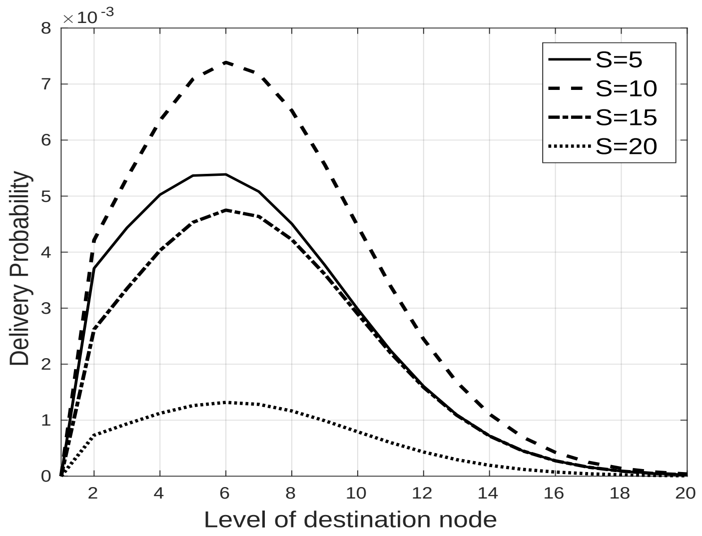

Figure 5.3.: Delivery probability for direct transmission from source to sink for different levels of destination

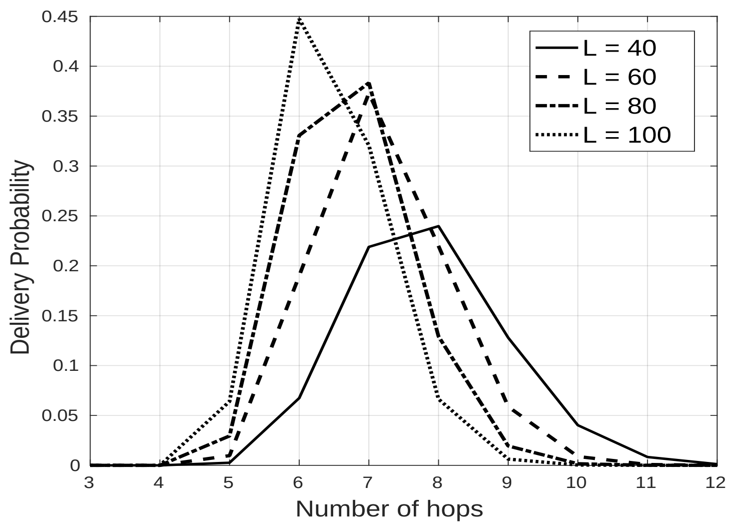

Figure 5.4.: Delivery probability for different total number of depth levels

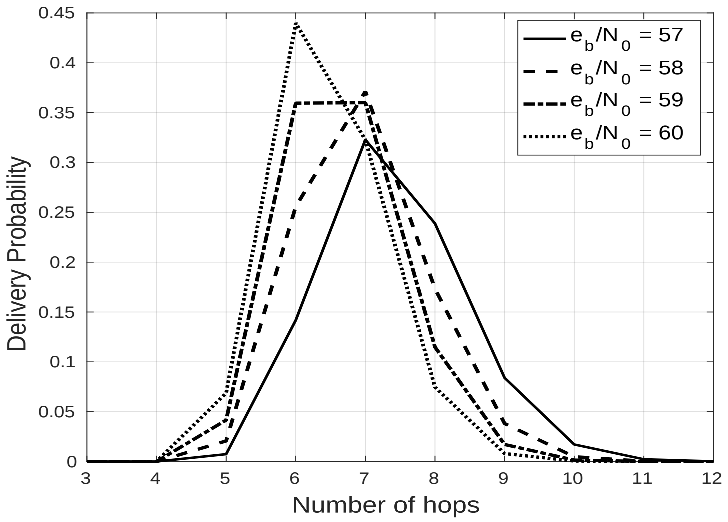

Figure 5.5.: Delivery probability for different e_b/N_0

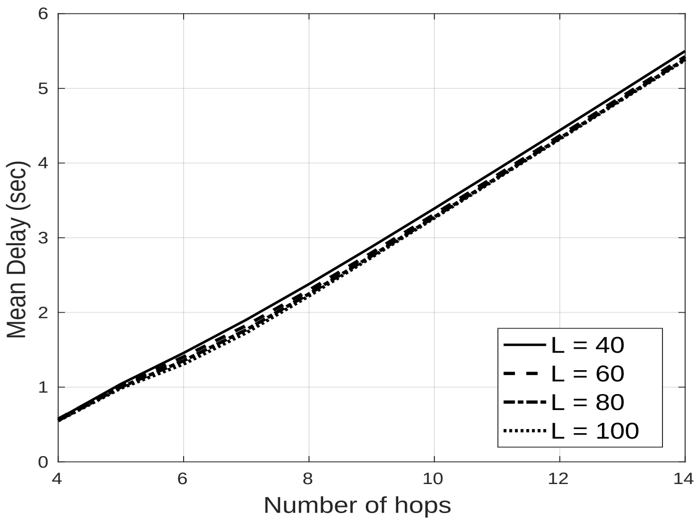

Figure 5.6.: Mean Delay for different total number of depth levels (sec)

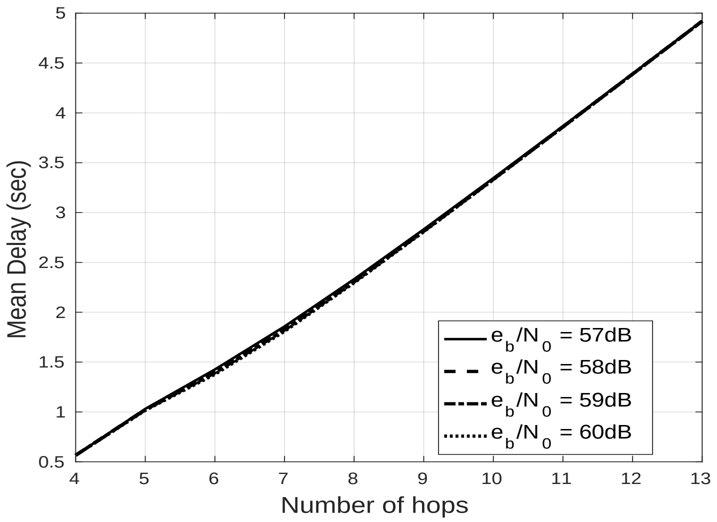

Figure 5.7.: Mean Delay for different e_b/N_0 (sec)

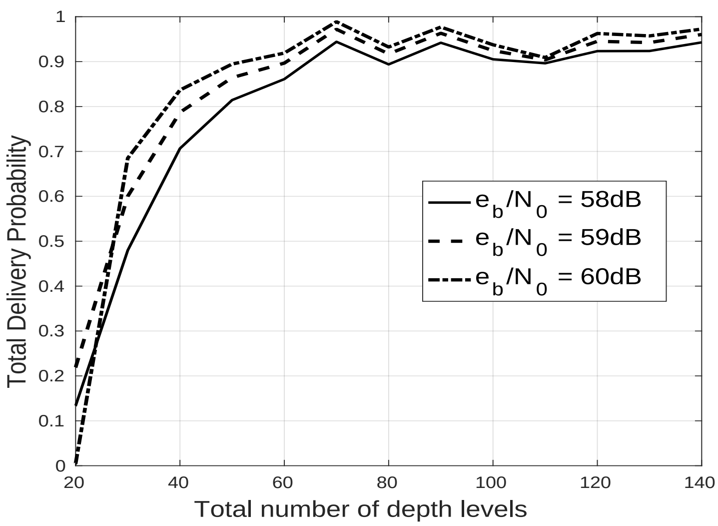

Figure 5.8.: Total delivery probability

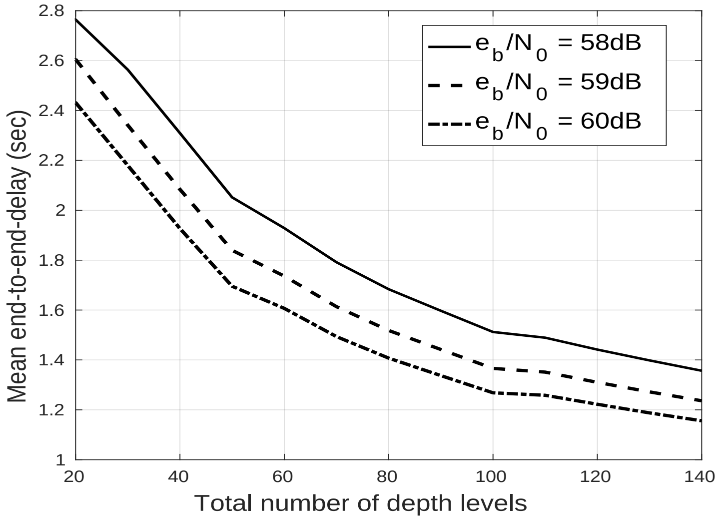

Figure 5.9.: Mean end-to-end delay (sec)

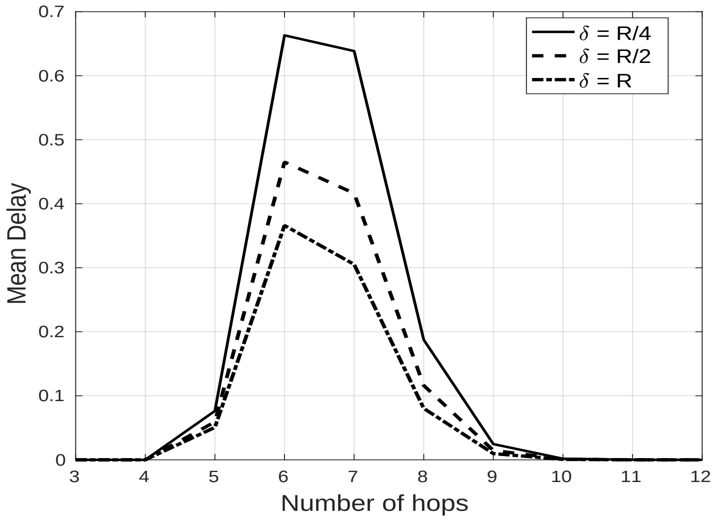

Figure 5.10.: Mean Delay (sec)

is small as it is likely that the packet will be delivered to higher nodes. The delivery probability therefore first increases with the depth level. However, if the depth level is already high, the chance to successfully transmit is low. Hence, the delivery probability decreases with increasing depth levels.

For the remaining plots, we assume that the node can move into $M = 15$ slots spanning a range $\Delta_W = 150$m. We set the transmission range to one-fifth of the total range of the network i.e., $T_r = \Delta_D/5 = 100$m and fix the position of the source and sink: $S = T = 10$.

We now focus on the number of hops needed for the data to be delivered at the sink. Note that the number of hops cannot exceed the number of depth levels as no downward transmissions are allowed in DBR. Fig. 5.4 and Fig 5.5 depict the probability mass function of the number of hops needed to deliver the packet from source to sink. In 5.4, we depict the probability mass function for networks with different levels L. In 5.5, we depict the probability mass function for different transmission powers e_b/N_0.

From the figures, we can observe that the delivery probability is zero for the first 4 hops which is not surprising as the transmission range is 100m. Moreover, most of the probability mass is between 5 and 9 hops, which is again in line with the transmission range. Finally, it is seen that end-to-end communication with fewer hops is more likely if there are more nodes (i.e., by increasing L, see Fig. 5.4), or if the transmission power increases (see Fig. 5.5).

5.5.2. Mean end-to-end delay

Fig. 5.6 depicts the mean delay conditioned on the number of hops required for the data to reach the sink. In this figure, we fixe e_b/N_0 to 57dB and show the mean delay for different number of depth levels L between the source and the sink. On the other hand, Fig. 5.7 fixes the number of depth levels to $L = 50$ and varies the transmission power as indicated. It is readily seen that the conditional end-to-end delay grows almost linearly with the number of hops, and is largely insensitive to changes in transmission power and the number of depth levels. This is not entirely unexpected as the end-to-end delay is largely dominated by the holding times at the nodes.

In Fig. 5.8 and Fig. 5.9, we depict the delivery probability at the sink and the corresponding mean end-to-end delay (conditional on the packet reaching the sink). We again set the total depth to $\Delta_D = 500$m and vary the number of depth levels. As we fix the total depth, increasing the number of levels means that the depth difference between adjacent levels decreases. Fig. 5.8 basically depicts the delivery probability at the sink vs. the number of depth levels for different e_b/N_0 as indicated. It can be seen from the figure that the total delivery probability in general increases when the number of depth levels increases. This is expected as we add additional sensors, making it less likely that the packet is lost. The curve is not monotone increasing though, which can be explained by the interplay between the depth levels and the fixed transmission range T_r. Fig. 5.9 shows that the mean end-to-end delay decreases when the number of depth levels increases. Moreover, while the delivery probability increases with e_b/N_0, it has the opposite effect on the mean end-to-end delay.

In Fig. 5.10, we study the effect of scaling parameter δ on the mean delay. The parameter δ is key for the holding times. Larger δ implies shorter holding times at each intermediate node and thus reduces the mean delay. This figure actually depicts the mean end-to-end delay, conditional on the number of hops. As previously noted, the end-to-end delay grows approximately linearly with the number of hops. It can now clearly be seen

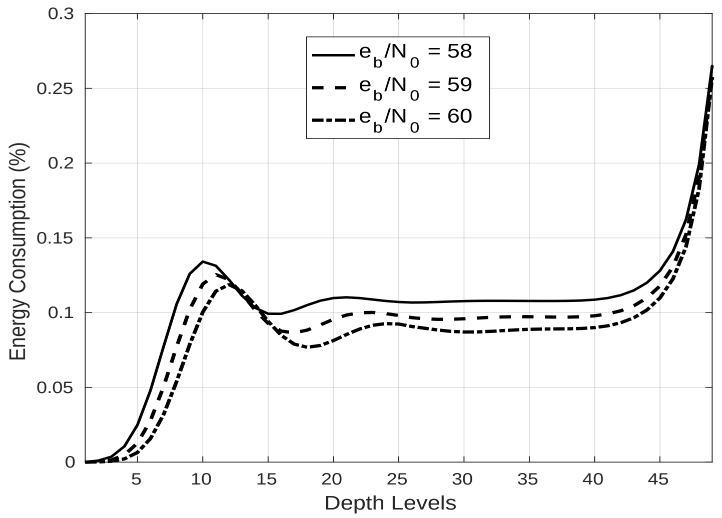

Figure 5.11.: Energy consumption (joules)

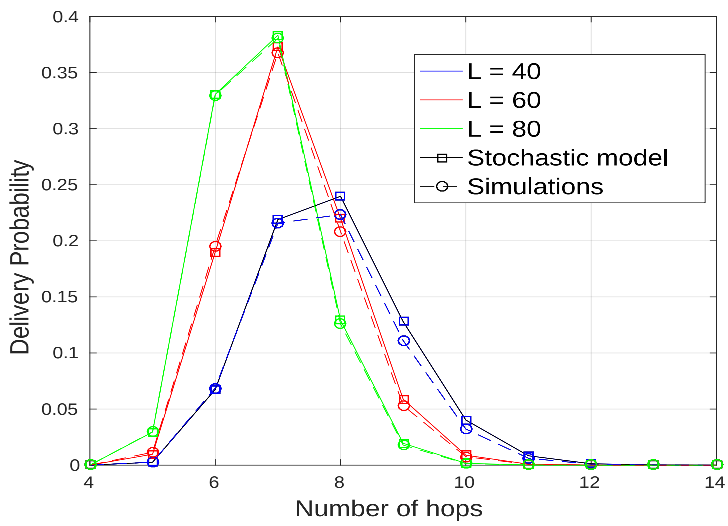

Figure 5.12.: Comparison of stochastic model and Monte-Carlo simulation for hops distribution

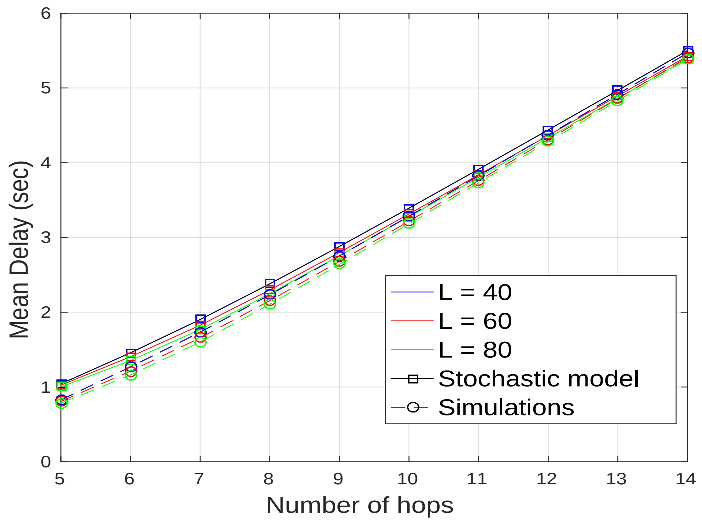

Figure 5.13.: Comparison of stochastic model and Monte-Carlo simulation for Mean delay (sec)

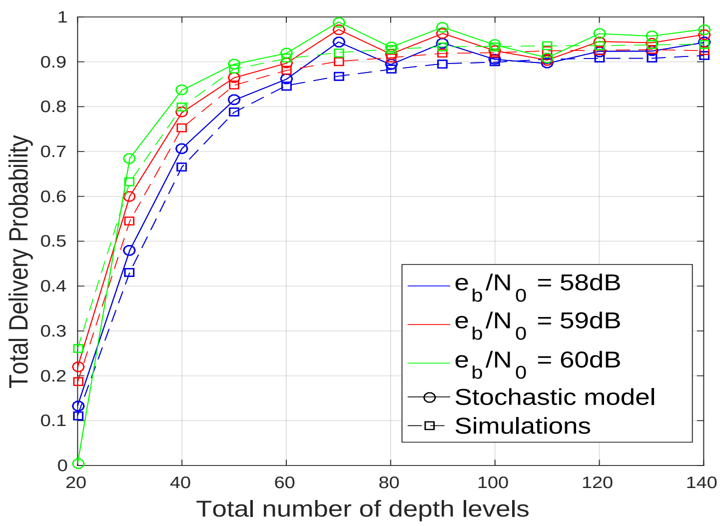

Figure 5.14.: Comparison of stochastic model and Monte-Carlo simulation for Total delivery probability

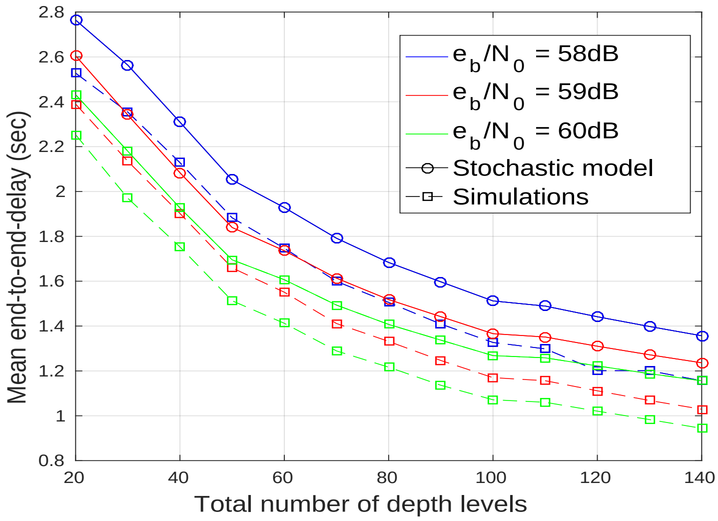

Figure 5.15.: Comparison of stochastic model and Monte-Carlo simulation for Mean end-to-end delay (sec)

that the slope of the conditional end-to-end delay depends on δ.

5.5.3. Energy consumption

Finally, Fig. 5.11 depicts the energy consumption at the different depth levels of the network. We assume that the amount of energy for one transmission is $\gamma = 1$, such that the plot depicts the mean number of times the nodes at each level participate in the transmission. Ideally, one aims for uniform energy expenditure such that the lifetime of all nodes is approximately equal. It is however clear from the figure that the energy consumption at levels close to both source and sink is higher, compared to the energy consumption by nodes in the middle of the network. This suggests that it is beneficial to increase the density of the nodes near sink and source.

5.5.4. Model validation by simulation

We now evaluate the performance of the model through simulations and compare the simulation results with the stochastic model. We keep the same size of the network: a depth of 500 m and a width of 150 m. At each iteration, we randomly deploy one node at each depth level, drawing the position from a uniform distribution. The positions of the nodes change from one iteration to the next iteration. The number of available positions that a node can take at a particular depth level are fixed to $M = 15$ in accordance with the stochastic model. Although the source and sink can be randomly located at bottom and surface level of the network respectively, we place them at a position 10 for consistency in the experiment. All the other network parameters are similar to those in stochastic model. Fig. 5.12 depicts the comparison of the hops distribution where Fig. 5.13 shows the comparison of the mean delay for different number of deployed nodes in the network. Furthermore, fig. 5.14 depicts the total delivery probability and fig. 5.15 shows the mean end-to-end delay for both the models. It can be seen from the figure that difference between the results of simulations and analytical model is negligible.

To compare the efficiency of the analytical model and the simulation model, we compare their time complexity. For the stochastic model, most of the time is spent on the calculation of the delivery probability and hops distributions. In the worst case scenario, the time complexity of the stochastic model is $O(L^3M^2)$, where L is the number of depth levels in the network and M is the number of positions that a node can take horizontally. For the Monte-Carlo simulations, we only simulate the positions of the nodes, and then calculate the performance measures by an analytic approach to reduce the variance of the Monte-Carlo simulation, see e.g. [74]. Hence, the time complexity of a single iteration is $O(L^3)$, which corresponds to the complexity of the stochastic model with $M = 1$ (as the nodes are at a fixed position in each iteration). For moderate M, the number of samples that are needed in the Monte Carlo simulations considerably exceeds M^2, which implies that the stochastic model can calculate the various performance measures faster.

5.6. Concluding remarks

In this chapter, we have proposed a numerically tractable stochastic model for the performance evaluation of DBR. Specifically, we have considered four performance indices: the hop-distribution, the packet delivery probability, the expected energy consumption and the expected end-to-end delay. The model has been validated by comparing the average performance indices obtained by its analysis with the estimates obtained from a stochastic simulation. By a numerical example, we have illustrated that our model can be used to assess the impact of various network configuration parameters (e.g., the transmission power and the scaling factor δ defined by DBR) on these indices. Our analysis showed that the number of hops in the route can dramatically affect the performance of the protocol. The proposed model can be further used for optimization purposes given the limited computational effort required, in comparison to underwater sensor network simulations.

6

On the Optimality of Opportunistic Routing Protocols for Underwater Sensor Networks

In the previous chapter, we have discussed a performance model of UWSNs equipped with DBR with the aim of assessing the impact of the transmission radius on a set of performance indices now, we focus on another parameter that characterises DBR implementation : the depth threshold. In this chapter, we make an important step to cover this gap. We study an abstraction of an opportunistic routing protocol and derive its optimal working conditions based on the network characteristics. Specifically, we prove that using a *depth threshold*, i.e., the minimum length of one transmission hop to the surface, is crucial for the optimality of opportunistic protocols and we give a numerical method to compute it. Moreover, we show that there is a critical depth threshold above which no packet can be transmitted successfully to the surface sinks in large networks, which further highlights the importance of properly configuring the routing protocol. We discuss the implications of our results and validate them by means of stochastic simulations on NS3.

6.1. Introduction

As discussed in the previous chapters, UWSNs pose several research challenges due to their peculiar characteristics: i) the low data rate and low speed of propagation due to the adoption of acoustic transmission , ii) the high mobility of the nodes, iii) the limited battery capacity of the motes and the difficulty in replacing or recharging them. Beside understanding the characteristics of the physical layer that are quite different from those of traditional radio-frequency based terrestrial networks (see e.g., [15, 72, 60]), designing efficient and reliable routing protocols is crucial for the development of these networks. To some extent, the routing protocols devised for UWSNs inherit some of the characteristics of those developed for vehicular networks, especially for those in which nodes are unaware of their position. In the UWSNs that we consider, the goal of routing is finding a multi-hop route from any underwater mote to the sonobuoys that float on the surface (see Figure 6.1). While flooding-based routing protocols such as the well-known AODV [11] cannot be adopted due to the high variability of the nodes's locations, in UWSNs we have the advantage that motes can easily estimate their depth thanks to onboard pressure sensors. Therefore, most of the protocols aim at devising a controlled flooding strategy (see, e.g., [13] and the references therein) with the objectives of covering the longest distance with one hop and reducing the total energy consumption of the network.

Opportunistic routing protocols for UWSNs are classified in *receiver-based* and *sender-based* [2] (See chapter 2). For receiver-based algorithms, a node that receives a packet decides if it is going to be a forwarder based on some factors among which the depth difference between itself and sender usually plays the major role (other factors may be the residual energy in a battery). Sender-based algorithms, on the other hand, are more difficult to implement and require the sender node to specify which neighbour node(s) will be the forwarder(s). In this chapter, we focus on receiver-based routing algorithms and assume that the only factor that is used to decide the forwarding is the depth difference between the sender and the receiver. This is the case for many protocols including the DBR that is still one of the mostly used protocols in actual implementations of UWSNs and is is adoped as benchmark for the performance evaluation of new routing protocols (see, e.g., [1, 46]).

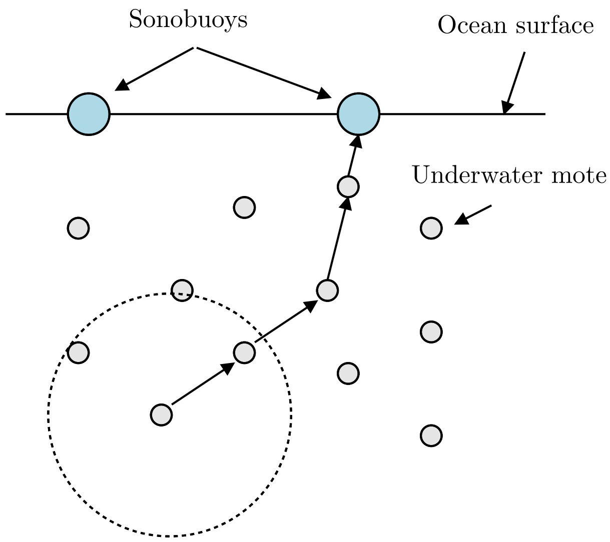

Figure 6.1.: Sketch of a UWSN.

6.2. Related work

In the recent literature on underwater networks, opportunistic routing protocols have been a topic of prime importance as they are able to handle high node mobility. However, while they quickly react to the continuous changes in the routes towards the on-surface sinks, opportunistic protocols may be quite energy consuming. Therefore, the optimal configuration of opportunistic routing protocols given the network characteristics is widely recognised as a research topic of crucial importance. This goal ca be achieved either by analytical modeling, possibly using formal descriptions of the system as in [75, 76, 77] or by simulation. Coutinho et al. [2, 10] provide a detailed survey of opportunistic routing protocols, and classify them on the basis of their forwarding mechanisms. They also suggest some important design guidelines for the distributed routing schemes. The classification of sender-based, receiver-based and holding time-based protocols points out their importance and suitability in context of the various underwater conditions.

In [78] the authors propose a stochastic model to evaluate the total energy consumption and end-to-end delay of a UWSN under ideal conditions, however the model considers cylindrical propagation instead of the more common spherical that we use here. In Pigneri et al. [38] the authors focus their attention on the impact of interference on the network's performance. With respect to our work, the analytical model that they propose does not consider the multi-hop routing protocol implementation.

Zhou et al. [22] propose a multipath communication model for UWSNs in which they compute the number of possible paths for transmission between the source node and the sink. In this model, they identify the optimal power consumption for the single packet delivery, under the assumption that a node knows some network parameters such as path length and the number of available paths. This may be hard to achieve in real deployments due to the node mobility.

Apart from UWSNs, analytical models have also been devised in the area of vehicular networks to optimize the performance of opportunistic routing protocols. Probably the closest work to what we propose here is [35]. The authors provide a qualitative argument about the optimality of threshold based routing algorithm for terrestrial networks on a line. The assumptions use are stricter than those considered here, and the mono-dimensionality of the scenario does not allow one to trivially extend the result. In fact, in [35] the eligible forwarders have full information about the distance with the source node, while in our case they know only one of the three components (the vertical one, i.e., the depth difference) of the three-dimensional vector representing their relative positions.

Aside from these works, many other papers (see, e.g., [50, 1, 46, 24]) address the problem of the performance evaluation and optimisation of UWSNs protocol by means of stochastic simulation. Unfortunately, simulating large networks can be very time consuming and makes their optimisation very hard especially because the parameters depend on several characteristics of the networks such as the node density, the transmission frequency, the encoding used, just to mention a few.

6.3. Contributions

In this section,we summarize the main findings presented in this chapter. Suppose that a node with depth difference x from the sender correctly receives a packet, and let $p(x)$ be the probability that it forwards it in the direction of the surface. In this scenario, our contributions as follows:

- The first problem that we address is the derivation of the optimal $p(x)$ conditioned on the expected number of forwarders ν. Having more than 1 expected forwarder may be useful to create redundant routes to the surface and to increase the packet delivery ratio. Our first finding is that the optimal form of $p(x)$ is threshold based, i.e., $p(x) = 1$ if the depth difference is above a certain threshold and $p(x) = 0$ otherwise. This result holds under very mild assumptions on the topology of the network, since we require only the stationarity of the point process modelling the nodes' positions.

- A second contribution consists in giving an analytical formula and a numerical algorithm for the computation of the optimal threshold when the nodes form a homogeneous Poisson point process (PPP). Interestingly, protocols like DBR already introduced the idea of a depth threshold under which nodes are not eligible forwarders but, to the best of our knowledge, this is the first time that the optimality of that choice is proved in the three-dimensional environment of UWSNs and that an efficient numerical approach for the computation of the optimal threshold is given. In fact, the derivation of the optimal threshold based on stochastic simulations may be very time consuming.

- The third contribution that we give is the estimation of the packet delivery probability given the expected number of forwarders for large UWSNs assuming a stationary PPP distribution of the nodes. We base our analysis on the theory of percolation on trees and derive a simple formula that, combined with the above mentioned results, allows one to fix a target packet delivery ratio and obtain the optimal threshold that allows that quality of service.

- Finally, we address a case study of a realistic UWSN and compare the analytical results with the simulations estimates obtained with Aquasim-NG simulator [3], a NS3 library for the analysis of underwater networks. The simulator was designed and verified by one of our previous research works [50] and provides a detailed simulation model of underwater sensors. The tool is open source and can be downloaded freely [49]. Interestingly, although the model does not take into account the mobility of nodes, the comparison with the simulations shows that it is robust with respect to node mobility. We discuss our detailed motivations also in Section 6.6.

Structure of the chapter This chapter is structured as follows. Section 6.4 proves the optimality of the threshold based form of the forwarding probability $p(x)$ and gives the algorithms for the computation of this threshold in the case of homogeneous Poisson processes. In Section 6.5, we relate the expected number of forwarders with the packet delivery probability by resorting to percolation theory. In Section 6.6, we assess the accuracy of our analytical model with respect to stochastic simulations performed in NS3. Finally, in Section 6.7, we give some final remarks. The work described in this chapter is going to appear in [79].

6.4. Threshold based optimisation

In this section we study an UWSN employing a threshold based opportunistic protocol (see, e.g., [24, 46, 1]). We study an abstract formulation of such protocols that works in this way: each node that correctly receives a packet decides if it forwards the packet based on the depth difference between the sender and the receiver. As mentioned before, in UWSNs, nodes can easily estimate their depth by means of pressure sensors but can hardly know their absolute location. The depth difference x between the sender and the receiver is computed thanks to the depth information that the sender inserts in the packet. Let $p(x)$ be the probability that a node with depth difference x from the sender will forward the packet, and let ν be the desired expected number of forwarders.

The main result that we prove in this section is that in order to maximise the distance to the surface covered by a transmission, $p(x)$ is always a step-function, i.e., $p(x)$ is 0 below a depth threshold T and is 1 otherwise. *This result is independent of the characteristics of the stochastic process modelling the locations of the nodes and of the function modelling the probability of a successful transmission.* We also provide a numerical method to compute the optimum threshold given the density of the nodes and the probability of error in the transmissions.

6.4.1. Modelling assumptions and goals

We consider an UWSN deployed in a three-dimensional space. The spatial process modelling the sensor deployment is arbitrary but motion-invariant. Each node is aware of its depth thanks to a pressure sensor embedded in the node and we assume the surface to be covered by sink nodes that collect the packets harvested underwater (e.g., sonobuoy). We aim at designing a stateless multi-hop routing protocol capable of connecting each sensor node with the surface.

The stateless multi hop protocol works as follows:

- A node n broadcasts a message with the harvested data and specifies its own depth in the packet
- All the nodes that potentially receive the message and whose depth is lower than that of the transmitter are candidate forwarders. Let us call this set of nodes $\mathcal{S}(n) = \{n_1, n_2, \ldots\}$

- Each node correctly receives the packet with a probability $f(d)$ that depends on the Euclidean distance between the sender and the receiver $f(d) : \mathbb{R}^+ \to [0, 1]$, with $f(d)$ strictly monotonically decreasing and

$$\lim_{d\to\infty} f(d) = 0\,;$$

- Each node $n_i \in \mathcal{S}$ that has correctly received the packet computes the depth difference Δ_i between itself and the sender and retransmits (i.e., forwards) the packet with a probability that depends only on this value. Let us call this probability $p(x) : \mathbb{R}^+ \to [0, 1]$, where x is the depth difference

We aim at determining $p(x)$ such that, given the expected number of forwarders ν, the expected distance covered in one transmission is maximised.

We assume that the nodes are distributed in $\mathbb{R}^3$ according to a point process (PP) Φ that satisfies some conditions that we will discuss hereafter. Φ is a countable random collection of points in $\mathbb{R}^3$. Let $\mathcal{B}^3$ be the Borel sets, then the σ-algebra consists of $\mathcal{B}^3$ with the Lebesgue measure. For each $B \in \mathcal{B}^3$, let $N(B)$ be the counting measure, i.e., a random variable associated with the number of nodes present in B. We define $\Lambda(B) = E\{N(B)\}$ as the intensity measure of Φ, and we assume it to be diffuse and to admit intensity function $\lambda(b)$ such that for each $B \in \mathcal{B}^3$:

$$\Lambda(B) = \int_B \lambda(b)db\,.$$

Φ is locally finite, i.e., for all B such that $|B| < \infty$ we have that $N(B) < \infty$, where $|B|$ is the Lebesgue measure of B. We assume Φ to be simple, i.e., $N(\{x\}) \in \{0, 1\}$ almost surely for all $x \in \mathbb{R}^3$, and stationary. As a consequence, $\Lambda(B) = \lambda|B|$ for some intensity $\lambda \in \mathbb{R}^+$.

Let $R \in \mathbb{R}^+$ be the transmission radius of a node n, i.e., we assume that for Euclidean distances larger than R the effect of the signal transmitted by n is negligible.

6.4.2. The model for general stationary point processes

Let us assume that the sender node is at location o. Let Φ_o be the PP obtained by conditioning on the presence of a point in o and that contains only the nodes that correctly receive the transmission from o. Formally, we are computing the reduced Palm distribution of Φ conditioned on o and then a thinning. Thus, Φ_o has diffuse density measure inside the sphere with radius R and centre o.

Since the nodes take their decisions of being forwarders based on the depth difference with the sender, we project Φ_o restricted to half-sphere with centre o and radius R on the vertical direction toward the surface, i.e., we consider the mapping function $\zeta : \mathbb{R}^3 \to [-R, R]$ and consider just the points in $[0, R]$:

$$\zeta(y) = y|_1 - o|_1 \tag{6.1}$$

where $y \in \mathbb{R}^3$, and $y|_1$, $o|_1$ denote the depth component of y and o, respectively. Now, let $\lambda_o(x)$ be the intensity function of this process. Then, the expected number of forwarders ν is given by:

$$\nu = \int_0^R \lambda_o(x)p(x)dx\,, \tag{6.2}$$

and the expected distance covered by one transmission is:

$$\ell = \int_0^R x\lambda_o(x)p(x)dx\,. \tag{6.3}$$

Given the expressions for ℓ and v, we want to determine the optimal function $p(x)$ which selects the relay nodes based on the depth difference that gives the desired expected number of forwarders and maximises the distance covered by a single hop transmission. The problem is solved in Theorem 6.4.1.

Theorem 6.4.1. *Given the optimisation problem:*

$$\begin{aligned} \textit{maximise:} \quad & \int_0^R x\lambda_o(x)p(x)dx && (6.4)\\ \textit{subject to:} \quad & 0 \le p(x) \le 1\,, && (6.5)\\ & \int_0^R \lambda_o(x)p(x)dx = v\,, && (6.6) \end{aligned}$$

where $\lambda_o(x)$ is strictly positive everywhere in $[0, R)$. Then, problem (6.4) has a unique solution $p^*(x)$ defined as follows:

$$p^*(x) = \begin{cases} 0 & \textit{if } x < T \\ 1 & \textit{if } x \ge T \end{cases}, \tag{6.7}$$

whenever there exists a T in $[0, R]$ such that:

$$\int_T^R \lambda_o(x)dx = v\,. \tag{6.8}$$

Proof. Let

$$\Lambda_o(x) = \int_0^x \lambda_o(u)du\,,$$

and observe that $\Lambda_o(x)$ is strictly monotoniccally increasing thanks to the assumptions on $\lambda_o(x)$ and let us define $t = \Lambda_o(x)$ which implies $dt = \lambda_o(x)dx$. Notice that $\Lambda_o(x)$ is monotoniccally increasing and hence invertible. Therefore, Equation (6.4) can be rewritten as:

$$\int_0^{\Lambda_o(R)} \Lambda_o^{-1}(t)p(\Lambda_o^{-1}(t))dt$$

and the constraints become:

$$\begin{aligned} 0 \le p(\Lambda_o^{-1}(t)) \le 1 \\ \int_0^{\Lambda_o(R)} p(\Lambda_o^{-1}(t))dt = v\,. \end{aligned}$$

Given $Z(t) = p(\Lambda_o^{-1}(t))$ we can rewrite the optimisation problem as:

$$\begin{aligned} \text{maximize:} \quad & \int_0^{\Lambda_o^{-1}(R)} \Lambda_o^{-1}(t)Z(t)dt && (6.9)\\ \text{subject to:} \quad & 0 \le Z(t) \le 1\,, && (6.10)\\ & \int_0^{\Lambda_o(R)} Z(t)dt = v\,. && (6.11) \end{aligned}$$

Now, since $\Lambda_o^{-1}(x)$ is also monotonically increasing as $\Lambda_o(x)$, the unique solution to the optimisation problem is:

$$Z(x) = \begin{cases} 0 & \text{if } x < T' \\ 1 & \text{if } x \geq T' \end{cases}$$

whenever there exists T' such that:

$$\int_{T'}^{\Lambda_o(R)} Z(t)dt = v \, .$$

Now, recall that $Z(x) = p(\Lambda_o^{-1}(x))$ and that $\Lambda_o^{-1}(x)$ is strictly monotonically increasing, therefore the optimum $p^*(x)$ must follow definition (6.7), where $T = \Lambda_o^{-1}(T')$. □

6.4.3. The model for homogeneous Poisson point processes

In the previous section we proved Theorem 6.4.1 for a general stationary PP. Now, we assume that Φ is a homogeneous Poisson point process (PPP) and provide a method for the computation of the optimal threshold T. Recall that a homogeneous PPP is motion-invariant, therefore Theorem 6.4.1 is still valid. In general, an analytical expression for T can be derived only for some instances of $f(x)$, whereas a numerical approach must be adopted in the other cases.

Let Φ be a homogeneous Poisson point process (PPP) with intensity λ, i.e., the number of nodes in each set $B \in \mathcal{B}^3$ has distribution:

$$Pr\{N(B) = k\} = \frac{(\lambda|B|)^k}{k!} e^{-\lambda|B|} \, ,$$

for $k \geq 0$, and for $B_1, B_2 \in \mathcal{B}$, such that $B_1 \cap B_2 = \emptyset$ we have that $N(B_1)$ is independent of $N(B_2)$. If we condition the process on the presence of a transmitting node at o, then, by Slivnyak's theorem [80, Thm. 8.10] the resulting Palm distribution does not change with respect to that of a PPP with the same intensity where we add a node in o. Without loss of generality, let us assume that o is at the origin of the axes. Following the lines of Section 6.4.2, we first obtain process Φ'_o with the process of thinning, i.e., we select the points that correctly receive the packet. A node at y receives the packet sent from the o with probability $f(||y||_2)$, where $||y||_2$ denotes the L2-norm of y. Notice that, we assumed that for $||y||_2 > R$, we have $f(||y||_2) = 0$. Therefore Φ'_o is a non-homogeneous point process in the sphere with centre o and radius R. More specifically, by the thinning theorem for PPPs [80, Thm. 2.36], since the thinning function depends only on the location of a point, then Φ' is a PPP with intensity function:

$$\lambda'_o(y) = \lambda f(||y||_2) \, .$$

Finally, we define another PP by mapping Φ'_o restricted to the half sphere that contains the points closer to the surface than o (i.e., those whose vertical components are positive). This mapping produces a non-homogeneous PPP in $[0, R]$ by the mapping theorem [80, Thm. 2.34] with intensity function:

$$\begin{aligned}\lambda_o(x) &= \int_0^{\sqrt{R^2-x^2}} 2 \int_{-u}^{u} \sqrt{\frac{u^2}{u^2-z^2}} \lambda' \left(x, z, \sqrt{u^2-z^2}\right) dz \; du \\ &= \int_0^{\sqrt{R^2-x^2}} 2 \int_{-u}^{u} \sqrt{\frac{u^2}{u^2-z^2}} \lambda f\left(\sqrt{x^2+u^2}\right) dz \; du = \int_0^{\sqrt{R^2-x^2}} 2\pi\lambda u f\left(\sqrt{x^2+u^2}\right) du \, .\end{aligned}$$

We can simplify the expression of the integral by a change of variable $\alpha^2 = x^2 + u^2$, i.e., $\alpha d\alpha = udu$, thus obtaining:

$$\lambda_o(x) = 2\pi\lambda \int_x^R \alpha f(\alpha) d\alpha\,. \tag{6.12}$$

Henceforth, we call

$$b(x) = \int_x^R \alpha f(\alpha) d\alpha\,,$$

and hence we can rewrite $\lambda_o(x) = 2\pi\lambda b(x)$.

6.4.4. Determining the optimal threshold for homogeneous PPPs

In order to determine the optimal threshold T, we need to solve Equation (6.8) in T. In the case of PPP, we can rewrite Equation (6.8) as:

$$\int_T^R b(x)dx = \frac{\nu}{2\pi\lambda}\,,$$

let $\nu_p = \nu/(2\pi\lambda)$. We can write $b(x)$ as:

$$b(x) = \int_0^R \alpha f(\alpha) d\alpha - \int_0^x \alpha f(\alpha) d\alpha\,.$$

If $f(\alpha)$ is continuous in $[0, R]$ we define $H(x)$ such that $H''(x) = xf(x)$. Notice that:

$$\int_0^y \int_0^x H''(\alpha) d\alpha dx = H(y) - H(0) - yH'(0)\,.$$

Thus, we can rewrite Equation (6.8) as:

$$\nu_p \;=\; R\int_0^R \alpha f(\alpha) d\alpha - \int_0^R \int_0^x \alpha f(\alpha) d\alpha \;\, dx - T\int_0^R \alpha f(\alpha) d\alpha + \int_0^T \int_0^x \alpha f(\alpha) d\alpha \;\, dx\,,$$

i.e., by using function $H(x)$:

$$\nu_p = R(H'(R) - H'(0)) - (H(R) - H(0) - RH'(0)) - T(H'(R) - H'(0)) + H(T) - H(0) - TH'(0)\,,$$

which reduces to:

$$H(T) - TH'(R) = \nu_p + H(R) - RH'(R)\,. \tag{6.13}$$

Observe that we can write the residual of Equation (6.13) as:

$$r(T) = H(T) - TH'(R) - \nu_p - H(R) + RH'(R)\,,$$

and hence:

$$\frac{\partial r(T)}{\partial T} = H'(T) - H'(R)\,.$$

Since $H'(x)$ is strictly monotonically increasing and $0 \le T \le R$, we conclude that $r(t)$ is monotonically decreasing in $[0, R]$ and hence it is particularly simple to find its unique root, if one exists.

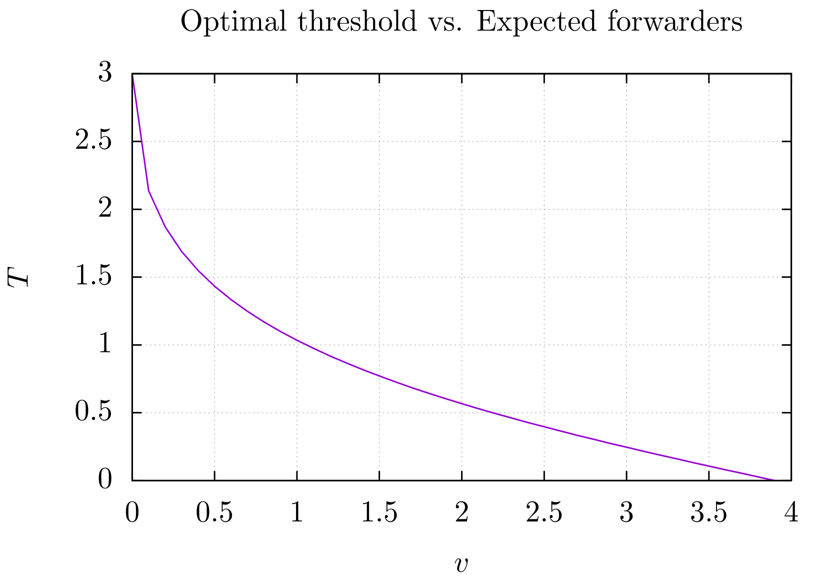

Figure 6.2.: Optimal threshold (T) as function of the expected number of forwarders for the model considered in Example 2 (km)

Proposition 6.4.1. *If the optimisation problem considered in Theorem 6.4.1 admits a solution, then this is unique.*

Therefore, whenever $H(R)$, $H'(R)$, $H''(R)$ have symbolic expressions, one may derive the optimal threshold easily.

Example 2 (Computation of the optimal threshold T)**.** *We consider an example in which the probability of correct packet reception decays exponentially with the Euclidean distance from the source node, i.e., $f(x) = e^{-ax}$ for some parameter $a > 0$. Then, we have:*

$$H''(x) = xe^{-ax}, \quad H'(x) = -\frac{e^{-ax}(ax+1)}{a^2}, \quad H(x) = \frac{e^{-ax}(ax+2)}{a^3}$$

Therefore, in order to find the optimal threshold we nee to solve the following non-linear equation:

$$e^{-\alpha T}\frac{\alpha T+2}{\alpha^3} + e^{-\alpha R}\frac{\alpha T + 2 - \alpha^2 R^2 + \alpha^2 RT - 2\alpha R + \alpha T + 2}{\alpha^3} - v_p = 0\,.$$

For instance, let us assume a network with a density of 2 nodes per km^3 and let $\alpha = 1.8$, with $R = 3km$. Notice that at $3km$ of distance, the probability of correct reception is $4.5 \cdot 10^{-3}$. Then, the optimal depth threshold T for having 2 expected forwarders is $T = 0.567km$. It is interesting to note that if the intensity is 1 node per km^3 then, with the same parameters, it is impossible to achieve the goal of 2 expected forwarders. In Figure 6.2 we show the optimal threshold T as function of the expected number of forwarders for this example.

In many practical cases, the symbolic expressions of $H(t)$ and $H'(t)$ are not known and hence the explicit or numerical solution of Equation (6.13) is not computationally feasible. Nevertheless, we can reconsider the original problem, i.e.:

$$r(T) = v_p - \int_T^R b(x)dx = 0,$$

and we recall that $r(T)$ is monotonic decreasing in $[0, R]$. Therefore, the solution for T may be easily numerically found thanks to the Newton-Raphson iteration scheme:

$$\begin{cases} T^{(0)} = \dfrac{R}{2}, \\ T^{(n+1)} = T^{(n)} - \dfrac{v_p - \int_{T^{(n)}}^{R} b(x)dx}{b(T^{(n)})}, \quad n \geq 0 \end{cases} \tag{6.14}$$

where at the denominator we need to numerically evaluate the integral:

$$\int_{T^{(n)}}^{R} \alpha f(\alpha) d\alpha,$$

while at the numerator:

$$\int_{T^{(n)}}^{R} \int_{x}^{R} \alpha f(\alpha) d\alpha dx,$$

that can be evaluated efficiently since the inner integrand function does not depend on x.

6.5. UWSN performance evaluation

In this section, we study the impact of the threshold on some performance indices of the network. The analysis relies on the following assumptions:

H1 The numbers of forwarders for each node are independent random variables;

H2 The network is sufficiently large to assume that it has an infinite number of nodes on a full three-dimensional space (i.e., nodes are not deployed on a plane);

H3 Nodes form a stationary PPP;

H4 The network protocol implements a perfect contention mechanism, i.e., the impact of collisions on the system's performance is negligible.

Hypothesis H1 tends to be verified thanks to the characteristics of UWSNs. In fact, the collision avoidance mechanism introduces some (possibly random) delays between the instant a node receives a packet and the moment in which this is forwarded (see e.g., [24]). As a consequence, if these delays are sufficiently large, the network topology may change between two different forwarding events. Finally, for dense networks, the number of nodes above the threshold that correctly receive the packet strongly depends on the probability of correct reception which is assumed to depend only on the distance. Hypotheses H2 and H3 are required to apply the percolation theory in order to estimate the packet delivery probability, and represent the typical scenario in this type of analysis. Finally, H4 is reasonable for delay tolerant UWSNs. There are several mechanisms that have been introduced to avoid collisions in redundant transmissions but before mentioning them we should recall that, in contrast with terrestrial wireless or wired networks [81], packets in UWSNs tend to be rather small, in the order of $300 - 400$ bits and that the transmission time has a non negligible component which depends on the low speed of propagation of the acoustic signal. In order to avoid collisions in the packet forwarding, most of the protocols tend to avoid carrier sensing with the aim of reducing the power consumption, however a statistical or deterministic contention of the channel may be adopted. In the statistical contention, the nodes wait for a random time before forwarding the packet. In this case, the trade-off is between larger delays that reduce the probability of collisions and short delays that improve the system's response time. Another approach is based on the introduction of a deterministic delay whose duration is inversely proportional to the depth difference between the sending and receiving nodes. With respect to the statistical contention, this approach tends to reduce the transmissions' end-to-end delay by favouring the transmissions of the relay nodes that cover the longest distance in the direction of the surface.

6.5.1. Percolation analysis

Let us consider the stationary PPP modelling the nodes' locations in the UWSN and, without loss of generality, let the sender be located at the origin of the axis. Let V^T be the r.v. modelling the number of forwarders when the depth threshold is T, then the following proposition holds:

Proposition 6.5.1. *Given a depth threshold T, let $E[V^T] > 0$, then V^T is a Poisson random variable with intensity ν.*

Proof. We already observed that the reduced Palm distribution obtained by conditioning on the location of the sender is still a stationary PPP with the same intensity of the original one by Slivnyak's theorem. We notice that, given T, the expected number of forwarders ν is given by Equation (6.2), and by hypothesis $\nu > 0$. Since the probability that a node is a forwarder depends only on its location, by the thinning theorem for PPPs, the resulting process is a (possibly non-stationary) Poisson process. As a consequence, the number of nodes in a finite region B is a Poisson random variable. If we take B as the half-sphere with radius R whose points are closer to the surface than the sender node, we know that its expectation is ν, and hence the distribution of the number of nodes is a Poisson r.v. with intensity ν. □

Thanks to hypotheses H1 and H2, we use percolation theory to estimate the packet delivery probability. Assume that at time epoch 0 the node located at the origin sends a packet. This is forwarded by V^T nodes, where V^T is a Poisson r.v. with intensity ν. Since the point process is stationary and thanks to H1 we can assume that the forwarding process in newly performed for each forwarder. Recall that, at each forwarding step, the relay nodes are closer to the surface than the sending node, i.e., the propagation of the packet is not monotone on the horizontal plane but is monotone in the direction of the surface. We estimate the packet delivery probability as the probability that the tree generated by the packet forwarding has infinite size.

Remark 3. *It is important to notice that the nodes forming the tree should not be intended as the nodes involved in the forwarding of the message, but rather as the transmissions involved. In fact, a node may be involved in the forwarding process multiple times. This is usually avoided in networks without node mobility, but it is a viable choice in UWSNs because of the high instability of the routes.*

Formally, let $Z_0 = 1$ be the initial transmission and Z_n the number of packet retransmissions that occur after n hops. Then, we have the following recursive relation:

$$Z_{n+1} = \sum_{i=1}^{Z_n} X_{n,i}\,, \qquad n \geq 0\,,$$

where $X_{n,i}$ is the random variable that models the number of forwarders of node i that transmitted after n hops. Clearly, by hypothesis, $X_{n,i}$ are i.i.d. random variables whose distribution is the same as V^T, i.e., a Poisson r.v. with intensity ν. Such a branching process is a Galton-Watson process [82]. The distribution of V^T is called offspring distribution.

We use the following two results:

1. If $\nu \leq 1$ then the branching process does not grow forever with probability 1;[1]

2. If $\nu > 1$ then the probability that the process does not grow forever is the minimum positive root of the equation $G(s) = s$, where $G(s)$ is the probability generating function of the offspring distribution. In our case, we need to find the minimum positive root η of the following equation:

$$e^{\nu(s-1)} = s\,, \tag{6.15}$$

   and the probability of correct packet delivery will be $1 - \eta$.

Example 3 (Packet delivery ratio and optimal threshold). *Let us consider again the network with the parameters introduced in Example 2. We desire to study the optimal threshold as function of the desired packet delivery probability p_s. Given p_s, we may find the corresponding expected number of forwarders by solving Equation (6.15) and hence the optimal threshold T by solving Equation (6.13) or by applying the Newthon Rhapson algorithm (6.14). We show in Figure 6.3 the results for this example. It is important to note that when the expected number of forwarders $\nu \leq 1$ then the packet delivery probability is* 0. *Therefore we can identify a critical value for the threshold T that allows the connectivity of the UWSN with positive probability (see Definition 6.5.1). In our case, the critical threshold is* $1.03474km$.

Definition 6.5.1 (Critical threshold). *The critical threshold for a UWSN is the threshold whose corresponding expected number of forwarders is* 1.

Clearly, for large UWSNs the depth threshold should never be higher than the critical threshold.

6.6. Numerical results and simulation

In this section, we consider a real world scenario and evaluate the accuracy of the proposed method with respect to the estimates obtained by means of stochastic simulations. We start with the description of the simulation model, and then show the results obtained. One pivotal element of our model is function $f(x)$, i.e., the probability that a packet is correctly received by a node placed at a distance x from the sender. The model for the computation of $f(x)$ has been discussed in detail in Section 4.3. In our setting, we used acoustic signals with $\nu = 10\,kHz$, so $a(\nu) = 1.1870\,db/km$. ν denotes the frequency of the signal whereas $a(\nu)$ is the absorption coefficient. We assume the binary shift keying modulation which is widely used in modern acoustic modems. Figure 6.4 shows the plot of $f(x)$ for the parameterization used in the simulations, when the transmission power is 140 db re μPa (see, e.g., [15]). As it is possible to see, we may take $R = 700m$.

[1] Notice that in our case the offspring distribution is Poisson and hence the deterministic case is excluded.

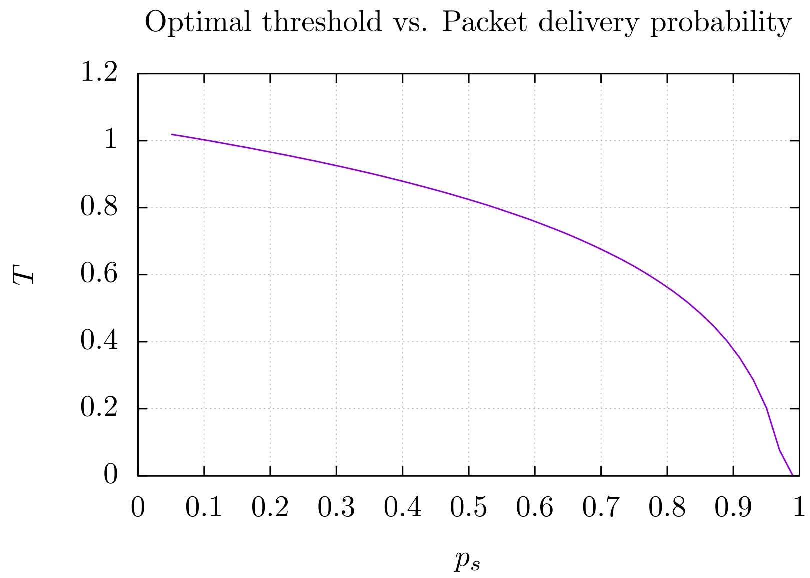

Figure 6.3.: Optimal threshold (T) as function of the packet delivery probability (km)

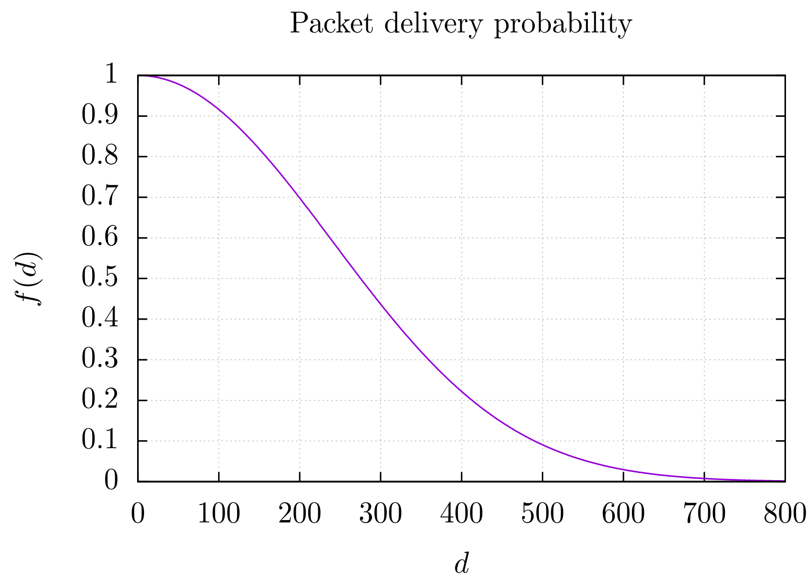

Figure 6.4.: Packet delivery probability in the simulation model. d is measured in m.

Parameter	Value
Network size	2000m ×2000m ×2000m
Deployment	Random uniform
Initial energy of nodes	100J
Packet size	40 Bytes
Transmission Range	700m
Node mobility speed	1 m/s, 3 m/s
Transmission power consumption	3.5 W
Receiving power consumption	0.1 W
Idle power consumption	1 mW
Mobility pattern	Gaussian Markov
Data rate	50 kb/s
Packet generation rate	0.5 packet/s
f	$10kHz$

Table 6.1.: Simulation Parameters

Other details of the simulation model In the network simulations, we use an UWSN with the routing protocol based on a threshold computed as discussed in Section 6.4. The simulation tool that we have used is specialised for underwater networks, namely AquaSim-NG [3], which is based on NS3 libraries [57]. The simulator accounts for the layered architecture of underwater network protocols and the operational modes of the modems. It is open source and freely downloadable from [49]. Packets are always sent from the bottom of the network at a rate of 0.5 packets per second. We use the broadcast MAC protocol implementation proposed in [62]. In order to minimize the congestion, we use the holding time computed as in DBR [24]. Four on-surface sink nodes have been deployed at random positions. Each estimate is the average of 15 independent experiments and in the plots we show the 98% confidence intervals. The details of the simulation parameters are shown in Table 6.1. Observing that, we followed the parameterisation proposed in [24] although commercial modems may have a smaller data rate. Nevertheless, numerous simulation experiments show that, under the remaining settings, this parameter does not significantly affect the packet delivery ratio.

Discussion of the results Figure 6.5 shows the packet delivery probability $p_s(T)$ as function of the threshold T obtained with the analytical model for three different node densities. As expected, higher node densities allow for higher depth thresholds, although the relation is not linear as shown in Figure 6.6. The plot of Figure 6.5 clearly shows the critical thresholds for the three densities. Furthermore, it is interesting to observe that the reduction in the depth threshold for increasing the packet delivery probability from 0.7 to 0.8 is lower than that required for passing from 0.8 to 0.9. This suggests that the number of redundant paths required to achieve a high packet delivery probability may be quite high.

Figure 6.7 shows the validation of the model against the stochastic simulation for two node densities. We observe that the model predictions are rather accurate, although the values of the packet delivery probability tends to be over-estimated when the depth threshold is low. We can explain this with the observation that we are assuming a perfect contention mechanism for the channel whereas, when the number of expected forwarders increases, the probability of hidden stations or interference with other delayed

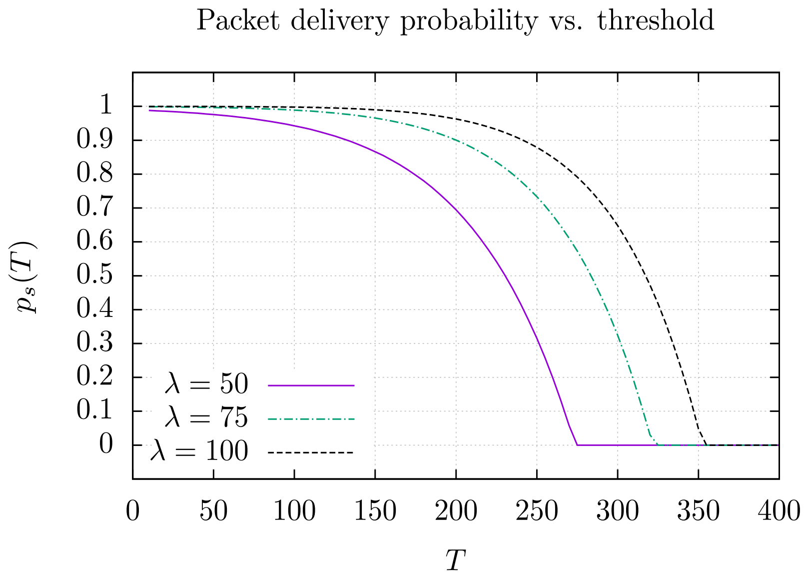

Figure 6.5.: Analytical results: optimal threshold and packet delivery probability for different values of the node density expressed in $nodes/km^3$, T is measured in m.

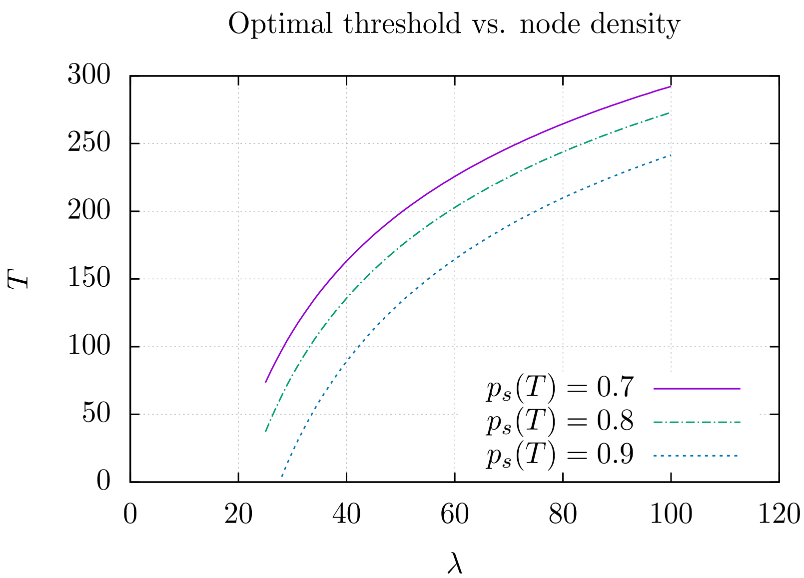

Figure 6.6.: Analytical results: optimal threshold as function of the node density for different target packet delivery probabilities. T is measured in m and λ in $nodes/km^3$.

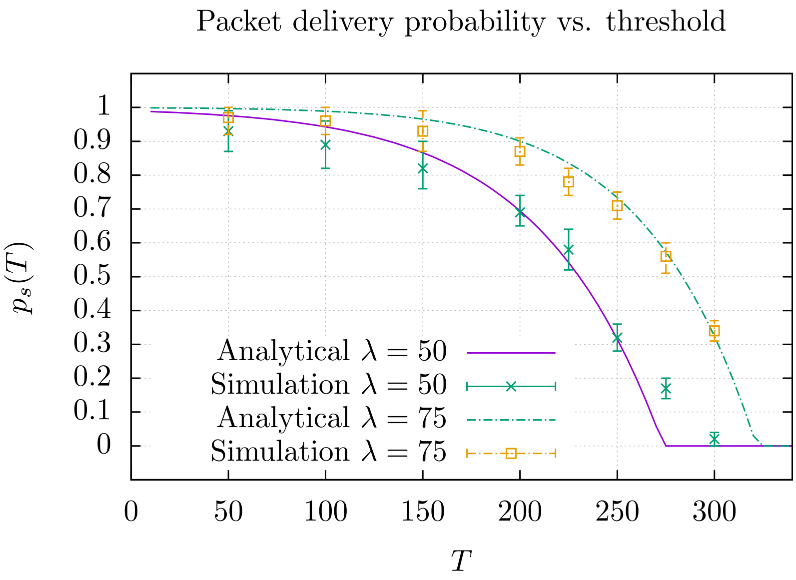

Figure 6.7.: Validation of the model: analytical results and Aquasim-NG estimates for $\lambda = 50$ and $\lambda = 75$ $nodes/km^3$. T is measured in m.

transmissions can worsen the system performance. Another important aspect to observe is that the simulation model takes into account the mobility of the underwater nodes. It may be surprising that the simulation estimates match closely the results of the analytical model that apparently does not contain any notion of mobility. We explain this effect by the *Displacement Theorem* for PPPs [Thm. 2.33][80] that basically states that in a PPP if the nodes are displaced by independent random vectors V_x at point x, then the resulting point process is still a PPP. Since we are using the stationary Gauss-Markov model [83], the conditions are satisfied and despite the mobility, the process of packet forwarding still occur in a different realization of the PPP but with the same statistics.

6.7. Concluding remarks

Most of the studies aimed at assessing the performance of routing protocols for UWSNs resort to stochastic simulations which are usually very time consuming. In many cases, network optimisations based on these simulations are computationally prohibitive. In this chapter, we propose an analytical model that allowed us to prove that the introduction of a depth threshold, similar to that proposed by DBR [24], is crucial for the definition of optimal routing protocols. The depth threshold T is used to control the number of forwarders by inhibiting the forwarding of the nodes whose depth difference with the sender is lower than T, and forcing it for all the nodes whose depth difference is above T. The analytical model allowed us to introduce an efficient method for the computation of the optimal depth threshold given a target packet delivery probability when the nodes' spatial distribution can be modelled by a homogeneous PPP. Despite the assumptions required by the model analysis, we showed that the NS3 based Aquasim-NG simulations show estimates of the packet delivery probability that are quite close to those derived analytically.

7

Analysis of performance in Depth-Based Routing for Underwater Wireless Sensor Networks

In this chapter, we continue our work on the formulation and the analysis of models for the optimisation in depth based routing. Here, we propose a stochastic analysis that aims at evaluating the performance of UWSNs using DBR in terms of expected energy consumption and expected end-to-end delay. Under a set of assumptions, we give expressions for these performance indices that can be evaluated efficiently, and hence they can be adopted as the basis for optimising the configuration parameters of the protocol.

7.1. Introduction

UWSNs share with their terrestrial counterparts some important factors including the high importance of energy preservation at the nodes. This need is due to the fact that nodes are autonomous and equipped with a battery that is difficult or expensive to replace. Some research efforts have been done in the direction of developing sensor nodes with the capability of harvesting energy from the environment, however the results seem to be still at their early stages [84, 85, 86]. In contrast with terrestrial wireless sensor networks, most of the UWSNs adopt acoustic communication instead of the traditional one based on radio-frequency. This implementation choice is due to the fact that acoustic communications cover long distances with low energy and are less prone to the problem of interferences. As a consequence, most of the methods developed for the performance evaluation of terrestrial networks (see, e.g., [87, 88, 75]) cannot be straightforwardly applied to underwater networks. Another characteristic of UWSN is that nodes are subject to high mobility caused by water currents. As a consequence, routing schemes that adopt the flooding strategy only in the routing discovery phase and then store the sequence of nodes to the destination in memory (e.g., [89]), are not applicable.

In the underwater scenario, routes continuously change and in most of the cases the best option is that of performing a controlled flooding for each packet transmission [2]. In order to tackle this problem, the DBR [24] aims to deliver the packets harvested in any part of the network to the sinks which float at the surface of the water also through controlled flooding. Moreover, once a node receives a packet that is stored in its holding queue, it removes the packet and cancels the corresponding holding time. In this way, for every transmission, DBR tries to maximise the distance covered avoiding collisions and redundant transmissions. There are several parameters that need to be set to configure a network employing DBR among which the major role is played by the transmission power. In the view of preserving the energy at the nodes, short transmissions seem to be more convenient, however we must take into account the fact that multiple forwarding will be required. Transmission power of a node depends on the distance required to cover through a single transmission [15]. On the other hand, long distance transmissions tend to drain the battery quickly.

In this chapter, we propose a model to study the impact of the transmission power on the total energy consumption of the network and on the end-to-end delay. The model is based on a set of results from the stochastic geometry research field [90] as well as on the manipulation of hypergeometric functions. We give detailed expressions for the expected energy cost and time cost per unit of distance of a certain transmission power. These expressions are extremely fast to evaluate and hence are appropriate for studying the optimal transmission power under certain network conditions.

The chapter is structured as follows. In Section 7.2 we discuss some related work. In Section 7.3, we briefly introduce the main features of DBR. Section 7.4 presents our

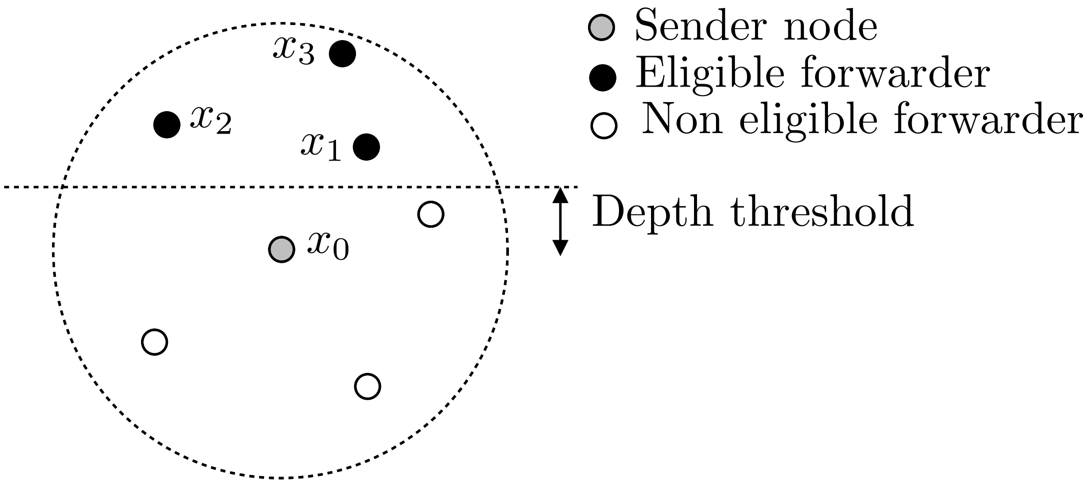

Figure 7.1.: Sketch of a transmission in DBR.

stochastic model and the derivation of the performance indices. In Section 7.5, we show some numerical results and illustrate an example of optimisation, and then Section 7.6 gives some final remarks. The work described in this chapter has been published in [78].

7.2. Related work

The following papers discuss the research results that are closely related to our findings. In [38] the authors optimize some performance indices for a generic multi hop protocol in UWSNs with respect to the optimal number of forwarding. With respect to this work, we focus on a specific protocol and solve the optimization problem based on its parameter configurations. In fact, given the optimal number of hops, it is not clear how one should configure the protocol parameters to reach that condition. In [39] the authors propose a performance evaluation of a Aloha-like communication protocol for UWSNs in a time-slotted setting. [65] proposes a Markovian model for a single acoustic channel but there is no consideration for the multi-hop behaviour of DBR.

7.3. Depth Based Routing

In this section, we briefly recall some salient features of DBR moreover, its comprehensive description has been given in chapter 3. DBR is an opportunistic routing protocol defined for UWSNs which works in a very simple manner. We give the explanation in the case of omnidirectional antennas following the schema of Figure 7.1. Recall that the goal of the model is that of delivering a packet to the nodes floating on the surface. Suppose that node x_0 transmits a packet that cannot reach the surface due to the limited transmission radius. The packet contains the depth of x_0 and each node that receives it correctly computes the depth difference between itself and x_0. One of the configuration parameters of the protocol is the depth threshold: every node whose depth difference is lower than the depth threshold is not an eligible forwarder. This parameter is used to prevent short range communications, but in some cases it can also assume negative values in order to avoid the problems connected with local minima in the network topology [1], i.e., situations in

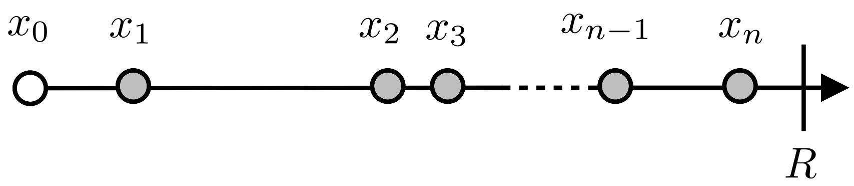

Figure 7.2.: Graphical representation of the model studied in Section 7.4.

which a node wants to transmit a packet to the surface and is at a lowest depth than its neighbours but cannot reach the surface in one step. In this work, we assume the depth threshold to be 0, i.e., we assume all the nodes that have lower depth than the sender to be eligible forwarders. Among the eligible forwarders we choose the forwarding node as follows: each node computes a delay whose duration is inversely proportional to the depth difference. This delay is called *holding time*. Then, the node behaves as follows: it keeps the packet in its holding queue for the duration of the holding time. If during this period it listens to a retransmission of the packet, then it cancels it from its holding queue otherwise, at its expiration, it forwards the packet. In an ideal situation this mechanism has two effects: it prevents packet collisions and redundant transmissions and chooses the node that is closest to the surface as packet forwarder in a completely distributed way. We assume the holding time mechanism to work in the ideal way, in other words a node with depth difference d will be a forwarder if and only if two conditions are satisfied:

1. It correctly receives the packet,
2. All the nodes that are closer to the surface than itself fail to correctly receive the packet.

In the example of Figure 7.1, node x_1 will be the forwarder if and only if it correctly receives the packet sent by x_0 while x_2 and x_3 fail.

7.4. A model for multi-hop protocol with directional antenna

We consider a model where a node x_0 sends a data packet in a certain direction (e.g., toward the surface). Following convention of DBR[24], We assume that the locations of the candidate relay nodes on that direction are independent and uniformly distributed (see Figure 7.2). If we assume that we have n potential relay nodes in a radius R, we can use the results from order statistics to characterise the distribution of the i-th node. Let $X^*_{(i)}$ be the random variable denoting the distance from x_0 to the i-th node, with $1 \leq i \leq n$. Then, the p.d.f. of $X^*_{(i)}$ is that of the marginal i-th order statistics of n independent uniform random variables in the real interval $(0, R)$ that corresponds to a rescaled Beta distribution:

$$f^*_{X_{(i)}}(x) = n\binom{n-1}{i-1}\frac{x^{i-1}(R-x)^{n-i}}{R^n},$$

where x is the distance from x_0. For practical purposes, we cannot characterise the exact number of nodes n in a distance R, but in many cases we know the expected density of the nodes. Hence, we let $n \to \infty$ and $R \to \infty$, as follows:

$$\lim_{\substack{n\to\infty \\ R\to\infty}} \frac{n}{R} = \delta, \tag{7.1}$$

where $\delta \in \mathbb{R}^+$ is the expected number of nodes per unit of distance (density) of the network. Now, let $X_{(i)}$ be the r.v. associated with the distance between x_0 and the i-th node, and let $f_{X(i)}$ be its p.d.f.

Proposition 7.4.1. *The p.d.f. of the location of the i-th node on the line in a network with density δ is given by:*

$$f_{X_{(i)}}(x) = \frac{\delta^i e^{-\delta x} x^{i-1}}{(i-1)!}. \tag{7.2}$$

Proof. We have to compute the limit:

$$\lim_{\substack{n\to\infty \\ R\to\infty}} f^*_{X_{(i)}}(x),$$

under the constraint (7.1). We can write:

$$\begin{aligned}
\lim_{\substack{n\to\infty \\ R\to\infty}} f^*_{X_{(i)}}(x) &= \lim_{n\to\infty} n\binom{n-1}{i-1}\frac{x^{i-1}(\frac{n}{\delta}-x)^{n-i}}{(\frac{n}{\delta})^n} = \lim_{n\to\infty}\frac{n!}{(i-1)!(n-i)!} \\
&\cdot \frac{x^{i-1}\left(\frac{n}{\delta}-x\right)^{n-i}}{\left(\frac{n}{\delta}\right)^n} = \frac{x^{i-1}}{(i-1)!}\lim_{n\to\infty}\frac{n!}{(n-i)!}\frac{\delta^i}{(n-\delta x)^i}\left(1-\frac{\delta x}{n}\right)^n \\
&= \frac{\delta^i x^{i-1}}{(i-1)!}\underbrace{\lim_{n\to\infty}\frac{n!}{(n-i)!(n-\delta x)^i}}_{1}\underbrace{\lim_{n\to\infty}\left(1-\frac{\delta x}{n}\right)^n}_{e^{-\delta x}} = \frac{\delta^i e^{-\delta x} x^{i-1}}{(i-1)!},
\end{aligned}$$

that completes the proof. □ Notice that,

according to Proposition 7.4.1 the p.d.f. of $X_{(i)}$ is that of a Gamma r.v. with shape i and rate δ. In other words, not surprisingly, we obtain a homogeneous Poisson point process on the line, where the distribution of the i-th distant node from the origin x_0 is given by the sum of i independent exponential r.v.s with rate δ.

The following proposition will play an important role in the analysis that we propose, since it gives the probability that all the nodes more distant than a certain threshold y fail to receive a packet sent by x_0.

Proposition 7.4.2. *The probability that all the nodes located after a certain threshold y fail to receive a packet sent by x_0 is:*

$$pf(y) = \exp\left(-\frac{\delta}{\lambda}e^{-\lambda y}\right). \tag{7.3}$$

Proof. Let us consider an arbitrary node whose location is conditioned in the interval (y, R), $y > 0$, $R \to \infty$, and recall that we are assuming that a node at distance x will

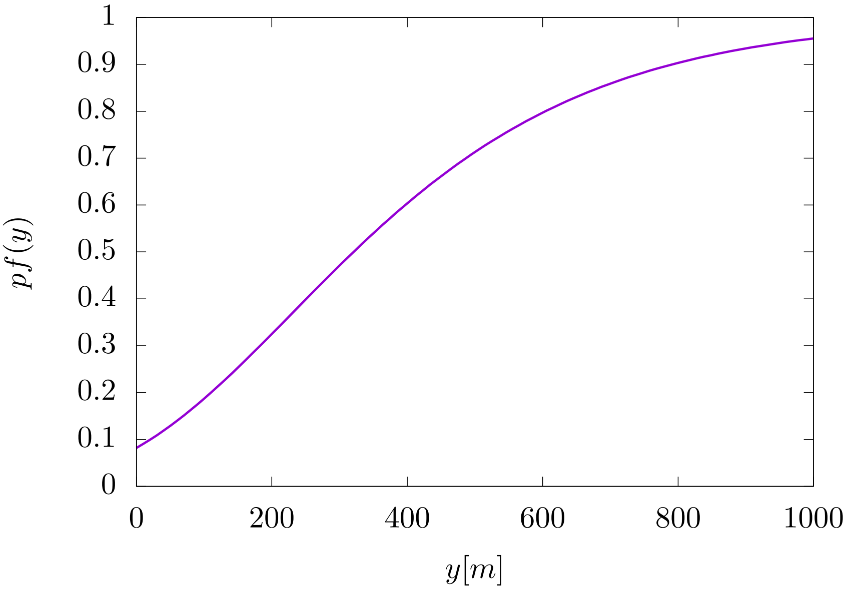

Figure 7.3.: Plot of the probability that none of the nodes more distant than y meters from x_0 correctly receives a packet sent from x_0.

successfully receive a packet sent by x_0 with probability $e^{-\lambda x}$, $\lambda > 0$ [1]. Then we have that the probability that such a node fails to receive a packet is:

$$pfs(y) = \int_y^R (1 - e^{-\lambda x}) \frac{1}{R - y} dx = 1 + \frac{e^{-\lambda R} - e^{-\lambda y}}{\lambda(R - y)} .$$

Therefore, we can compute the probability that all the nodes are farther than y from x_0 fail to receive a packet (recall that both the location and the events of correct packet reception are independent) and let $R \to \infty$:

$$pf(y) = \lim_{\substack{n \to \infty \\ R \to \infty}} \left(1 + \frac{e^{-\lambda R} - e^{-\lambda y}}{\lambda(R - y)}\right)^n ,$$

that under the constraint (7.1) can be written as:

$$pf(y) = \lim_{n \to \infty} \left(1 + \frac{e^{-\lambda \frac{n}{\delta}} - e^{-\lambda y}}{\lambda(\frac{n}{\delta} - y)}\right)^n ,$$

and rewritten as:

$$\lim_{n \to \infty} \left(1 + \frac{e^{-\frac{\lambda}{\delta} n}\delta}{\lambda n - \lambda y \delta} - \frac{1}{n} e^{-\lambda y} \frac{\delta}{\lambda - \frac{\lambda y \delta}{n}}\right)^n .$$

Now the proof the proposition follows easily. □

Example 4. *Let us consider a network in which the probability of correct reception at* $250m$ *is* $1/e$*, i.e.,* $\lambda = 1/250$ *in a network with a density of* 10 *nodes per km, i.e.,* $\delta = 0.01$ *nodes per meter.*

In Figure 7.3 we show the probability that all the nodes after a certain y fail to receive a packet sent by x_0*,* $pf(y)$*.*

Notice that by setting $y = 0$ in Equation (7.3) we can compute the probability that all the nodes fail to receive the packet as:

$$pf(0) = e^{-\delta/\lambda} . \tag{7.4}$$

Now recall that i-th node will be the forwarder of a packet if and only if the following conditions are satisfied:

1. Node i, placed at $X_{(i)}$, correctly receives the packet from x_0;

2. All the nodes $X_{(i+1)}$, $X_{(i+2)}$, ... fail to receive the packet.

Hence, the probability P_i that the forwarder will be the i-th node is:

$$P_i = \int_0^\infty f_{X_{(i)}}(x) e^{-\lambda x} pf(x) dx , \tag{7.5}$$

which can be obtained by the independence assumption of the event of correct reception of a packet. Since $E[X_{(i)}] = i/\delta$, we have that the expected distance covered by a transmission is:

$$\overline{L} = \frac{\sum_{i=0}^{\infty} i P_i}{\delta} .$$

Unfortunately, it is not easy to find a closed form expression for P_i, but since we are interested just in an expectation we can proceed as follows. Let T be the r.v. that takes value i with probability P_i, then we have:

$$\overline{L} = \frac{E[T]}{\delta} .$$

The following proposition gives the expression for $E[T]$ and hence for $\overline{L}$.

Theorem 1. *In a network with density δ and probability of correct reception $e^{-\lambda x}$, with x the distance between source and destination, the expected distance coveted by a transmission is $E[T]/\delta$ where the expected forwarder in the network $E[T]$ can be computed as:*

$$E[T] = 1 - e^{-\delta/\lambda} + \frac{\delta}{\lambda} \left(\gamma + E_1 \left(\frac{\delta}{\lambda} \right) + \log \left(\frac{\delta}{\lambda} \right) \right) ,$$

$\gamma \simeq 0.577216$ *is Euler's constant, and*

$$E_1(x) = \int_x^\infty \frac{1}{t} e^{-t} dx ,$$

is the exponential integral function [91, Ch. 6.2].

Proof. We compute $E[T]$ as $\sum_{i=1}^{\infty} Pr\{T \geq i\}$. For $i \geq 2$ by conditioning on the position x of the $(i-1)$th node the probability that at least one node in (x, ∞) will retransmit the packet, i.e.:

$$Pr\{T \geq i\} = \int_0^\infty f_{X_{(i-1)}}(x)(1 - e^{-\frac{\delta e^{-\lambda x}}{\lambda}}) dx , \quad i \geq 2 \tag{7.6}$$

while $Pr\{T \geq 1\} = 1 - e^{-\delta/\lambda}$. Integral (7.6) can be shown to converge to $1 - {}_{(i-1)}F_{(i-1)}(\mathbf{a}; \mathbf{b}; z)$ where

$$\mathbf{a} = \left(\frac{\delta}{\lambda}, \ldots, \frac{\delta}{\lambda} \right)$$

and

$$\mathbf{b} = \left(1 + \frac{\delta}{\lambda}, \ldots, 1 + \frac{\delta}{\lambda}\right)$$

and $c = -\delta/\lambda$.

Remark 4. *The generalized hypergeometric function* ${}_pF_q(\mathbf{a}, \mathbf{b}; z)$*, where* $\mathbf{a} = (a_1, \ldots, a_p)$*,* $\mathbf{b} = (b_1, \ldots, b_q)$*, is defined as:*

$$ {}_pF_q(\mathbf{a}, \mathbf{b}; z) = \sum_{n=0}^{\infty} \frac{(a_1)n \cdots (a_p)_n}{(b_1)_n \cdots (b_q)_n} \frac{z^n}{n!}, \tag{7.7}$$

where $\mathbf{a} \in \mathbb{R}^p$*,* $\mathbf{b} \in \mathbb{R}^q$*,* $z \in \mathbb{C}$ *and* $(a_i)_0 = 1$*,* $(a_i)_n = a(a+1)\cdots(a+n-1)$ *is the Pochhammer's symbol. It is well-known that if* $p < q + 1$ *then the series converges (absolutely) for any finite z [91, Ch. 16]. In our case, we have* $p = q = i - 1$ *and hence the convergence is proved.*

Now, by using the definition of generalised hypergeometric series (see Equation (7.7)), we can rewrite Integral (7.6) as:

$$Pr\{T \geq i\} = 1 - \sum_{k=0}^{\infty} \left[\frac{(\delta/\lambda)_k}{(1+\delta/\lambda)_k}\right]^{i-1} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!} = 1 - \sum_{k=0}^{\infty} \left(\frac{\delta}{\delta + k\lambda}\right)^{i-1} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!}.$$

Notice that the last expression for $i = 1$ gives exactly $1 - e^{-\delta/\lambda}$ and hence we can extend its validity for $i \geq 1$. By noting that $Pr\{T = i\} = Pr\{T \geq i\} - Pr\{T \geq i + 1\}$, and since the series are absolutely convergent, we have:

$$Pr\{T = i\} = \sum_{k=0}^{\infty} \left(\frac{\delta}{\delta + k\lambda}\right)^{i-1} \left(-\frac{\delta}{\lambda}\right)^k \left(\frac{-k\lambda}{\delta + k\lambda}\right) \frac{1}{k!}.$$

Let us now compute $E[T]$:

$$E[T] = \sum_{i=1}^{\infty} Pr\{T \geq i\} = \sum_{i=1}^{\infty} \left(1 - \sum_{k=0}^{\infty} \left(\frac{\delta}{\delta + k\lambda}\right)^{i-1} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!}\right)$$

that can be rewritten as:

$$\sum_{i=1}^{\infty} \left(1 - 1 - \sum_{k=1}^{\infty} \left(\frac{\delta}{\delta + k\lambda}\right)^{i-1} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!}\right) = -\sum_{k=1}^{\infty} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!} \sum_{i=1}^{\infty} \left(\frac{\delta}{\delta + k\lambda}\right)^{i-1}.$$

Observe that $\delta/(\delta + k\lambda) < 1$ by hypothesis and hence we can write:

$$E[T] = -\sum_{k=1}^{\infty} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!} \left(\frac{\delta + \lambda k}{\lambda k}\right). \tag{7.8}$$

We can rewrite Series (7.8) as:

$$E[T] = -\left(\sum_{k=1}^{\infty} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!}\right) - \left(\sum_{k=1}^{\infty} \left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!k} \frac{\delta}{\lambda}\right).$$

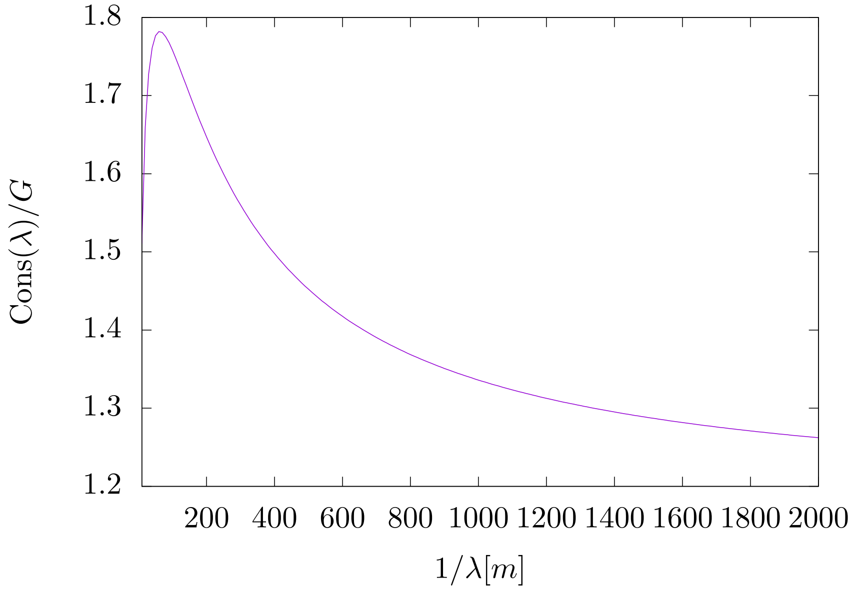

Figure 7.4.: Expected energy consumption per unit of distance for $\alpha = 1.2$

From the observation that:

$$\sum_{k=1}^{\infty}\left(-\frac{\delta}{\lambda}\right)\frac{1}{k!} = e^{-\delta/\lambda} - 1$$

and by [91, Eq. 6.6.2]:

$$\sum_{k=1}^{\infty}\left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!k}\frac{\delta}{\lambda} = \frac{\delta}{\lambda}\sum_{k=1}^{\infty}\left(-\frac{\delta}{\lambda}\right)^k \frac{1}{k!k} = -\frac{\delta}{\lambda}\left(\gamma + \log\left(\frac{\delta}{\lambda}\right) + E_1\left(\frac{\delta}{\lambda}\right)\right),$$

the theorem is proved. □

7.4.1. Analysis of the energy consumption

In the light of Theorem 1 we can draw some conclusions on the optimal transmission power for the sender node. Recall that the probability for a node to correctly receive a packet sent at distance d is $e^{-\lambda d}$, i.e., high values of parameter λ model a system in which the expected transmission length is short. We model the energy consumed for a transmission as function of λ as follows:

$$\mathrm{En}(\lambda) = G\frac{1}{\lambda^{\alpha}}, \tag{7.9}$$

where G is a normalising constant, and α is a parameter that depends on some environmental factors like the depth of the node, the salinity and the spreading coefficient [59]. Indeed, in underwater networks, the transmission power is consumed by the spreading of the signal and by its attenuation. The latter factor depends on the frequency adopted by the network as stated by Thorp's formula [60], but it tends to be lower for lower frequencies. The spreading coefficient, is lower than that of terrestrial networks, i.e., its value is between 1 and 2. In our case we can assume $\alpha > 1$, and we compute the expected

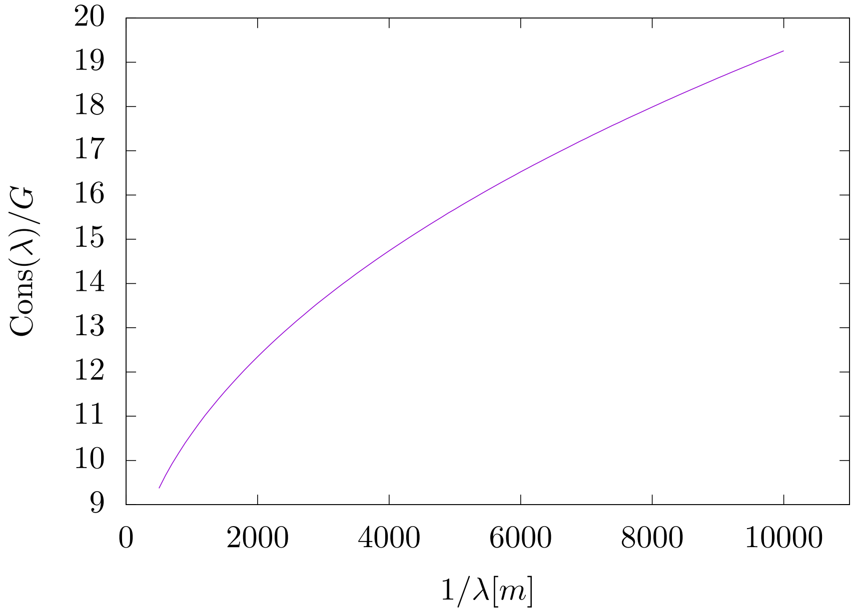

Figure 7.5.: Expected energy consumption per unit of distance for $\alpha = 1.5$

energy consumption for unit of distance as:

$$\text{Cons}(\lambda) = \frac{En(\lambda)}{\overline{L}},$$

where $\overline{L}$ is computed thanks to Theorem 1. It can be shown that for $\alpha > 1$ (which is the case for practical scenarios), we have that $\text{Cons}(\lambda) \to 0$ as $\lambda \to \infty$, whereas $\text{Cons}(\lambda) \to \infty$ as $\lambda \to 0$. This confirms the idea that, from the point of view of the energy consumption, it is more convenient to perform many multi hop short transmissions rather than long transmissions. However, as we will see in Section 7.4.2, the energy consumption is not the only requirement of an UWSNs, i.e., we have to consider also the problem of the end-to-end delay. Short transmissions require the packet to be sent multiple times for a correct reception and the multi-hop mechanism used by protocols such as DBR requires to wait for the holding time to expire at each forwarding/retransmission step.

We will study the trade off between energy saving and low end to end delay in the following sections. In Figure 7.4 and 7.5 we show the plots of $\text{Cons}(\lambda)/G$ for some practical values of $\alpha = 1.2$ and $\alpha = 1.5$ [92]. Notice that in the first plot the function still tends to ∞ for $\lambda \to 0$ even if the scale has been chosen to show the maximum around 100.

7.4.2. Analysis of the end-to-end delay

In this section we introduce a performance index that measures the speed at which a packet is forwarded in the network. To this aim, we measure the expected time required by a packet to cover a unit of distance. Notice that when none of the eligible forwarders correctly receives the packet sent by x_0 this has to be resent and the holding time must be newly waited.

Let τ be the time required by the transmission of the packet. Then, the expected time to cover a unit of distance is given by:

$$\text{Time}(\lambda) = \frac{\text{Tr}(\lambda)\tau}{E[L|\text{correct transmission}]}, \tag{7.10}$$

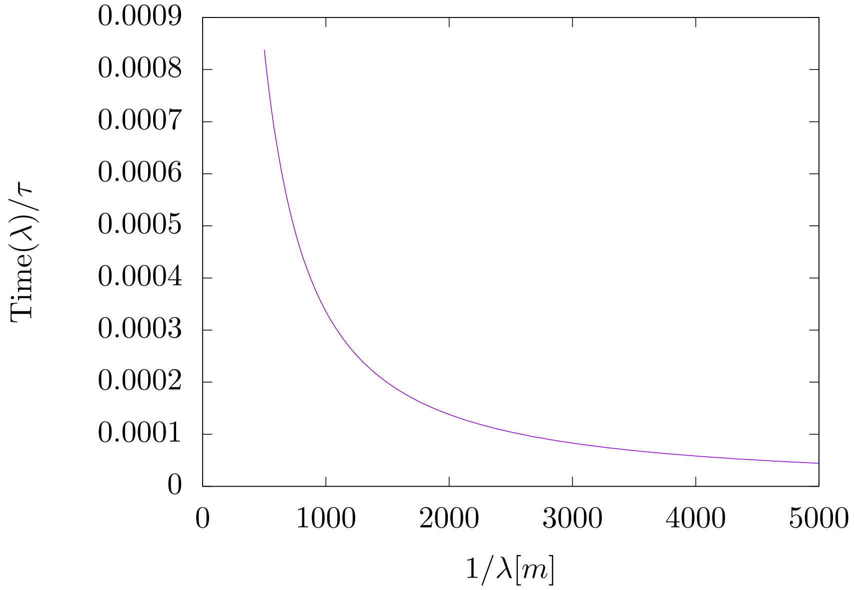

Figure 7.6.: Expected time per unit of distance for $\alpha = 1.5$

i.e., the expected number of transmissions $\mathrm{Tr}(\lambda)$ required to get a successful packet forwarding multiplied by the time required by each transmission and divided by the conditional expectation of the distance covered by one transmission. By the independent assumption, $\mathrm{Tr}(\lambda)$ is the expected value of a geometric random variable whose failure probability is given by Equation (7.4). Equation (7.4) can be used also for the computation of the conditional expectation and after simplifying Equation (7.10) we obtain:

$$\mathrm{Time}(\lambda) = \frac{\tau}{L}\,.$$

In Figure 7.6 we show the plot of $\mathrm{Time}(\lambda)/\tau$ for $\alpha = 1.5$. As expected, we have that:

$$\lim_{\lambda\to\infty} \mathrm{Time}(\lambda) = \infty\,, \quad \lim_{\lambda\to 0} \mathrm{Time}(\lambda) = 0\,.$$

7.5. Numerical evaluation and optimisation

In this section we study a simple instance of optimization problem. From the previous sections, we observed that from the point of view of the expected energy consumption it is more convenient to perform multiple transmissions with small range to deliver a packet, whereas in order to minimize the end-to-end delay we should maximise the transmission power. We can study this trade off by introducing a cost function defined as the linear combination of these two performance indices:

$$\mathrm{Cost}(\lambda) = a \cdot \mathrm{Cons}(\lambda) + b \cdot \mathrm{Time}(\lambda)\,,$$

where $a, b \geq 0$ are some weight constants. Considering that the propagation speed of acoustic signals in the underwater environment is $v_0 = 1500m/s$, we take $2s$ for the sum of the holding time and the sending time. Since the energy consumption strongly depends on the technical implementation of the acoustic modems, we assume as basic unit of measure for the energy, the energy ϵ required to have $1/\lambda = 100m$, which implies $G = 1000$.

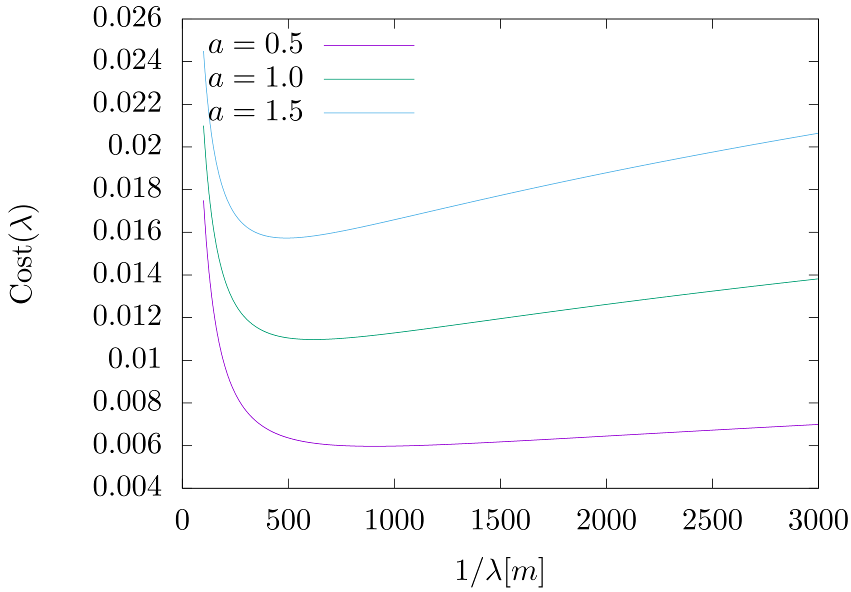

Figure 7.7.: Cost function for the example of Section 7.5

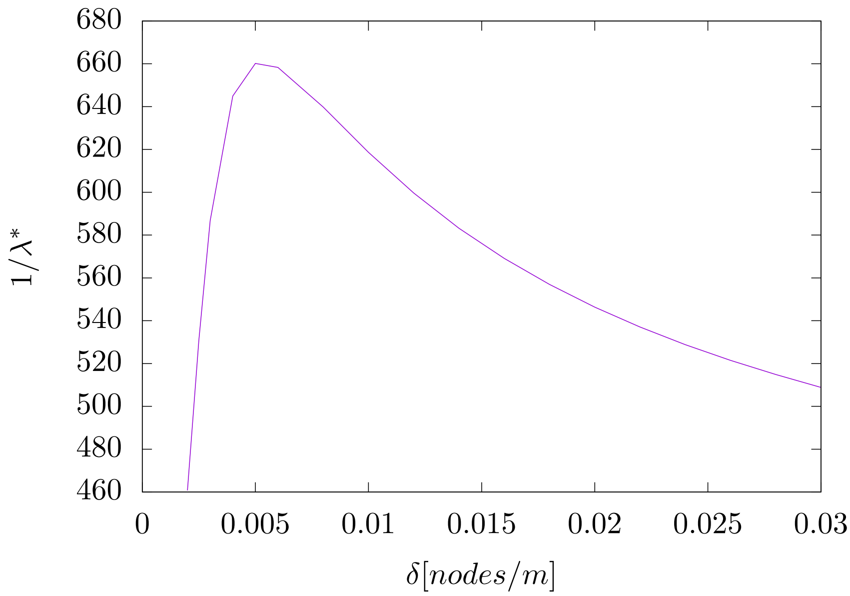

Figure 7.8.: Solution of the optimisation problem (7.11)

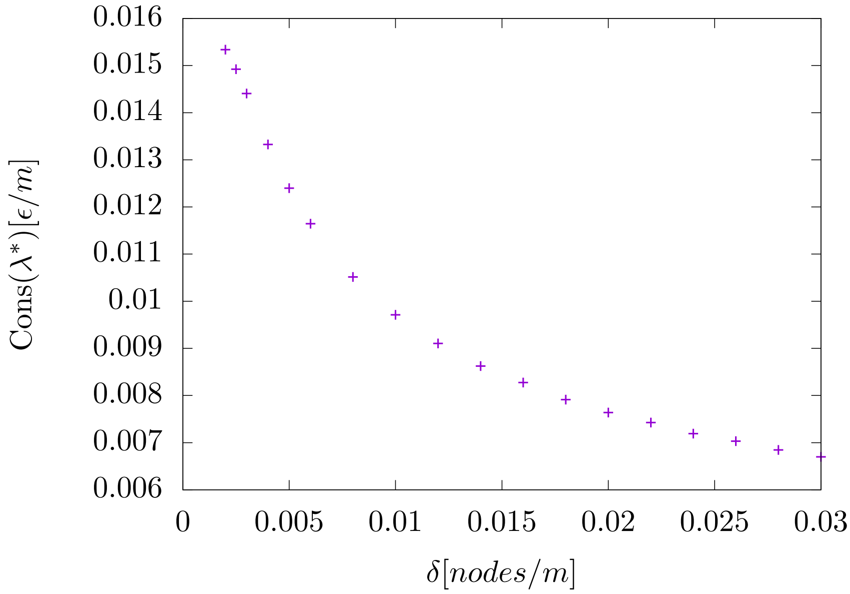

Figure 7.9.: Expected energy consumption per unit of distance for the optimal configuration.

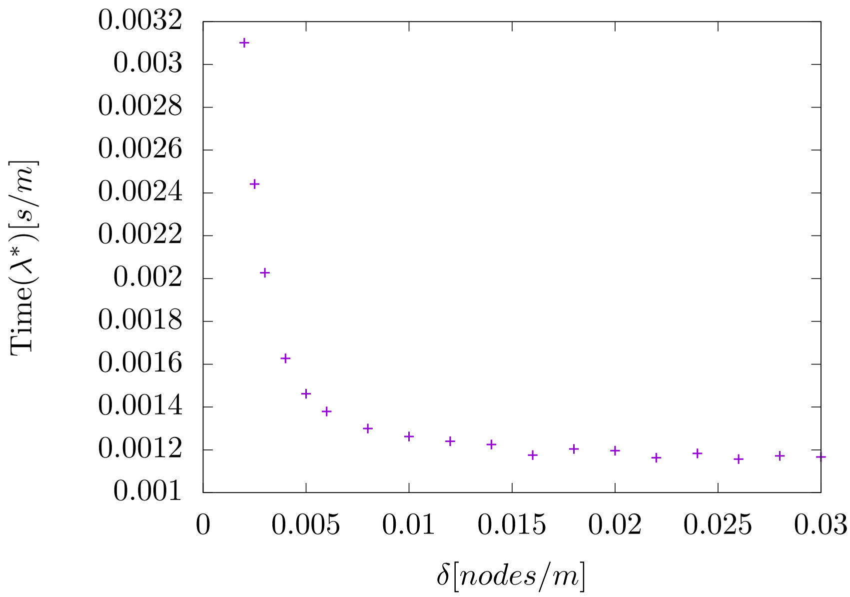

Figure 7.10.: Expected delay per unit of distance for the optimal configuration.

We take $b = 1m/s$ and a varying from $0.5m/\epsilon$ to $1.5m/\epsilon$. In Figure 7.7 we show the graphical solution to the optimisation problem. Unfortunately, the minimisation of the cost function does not admit an explicit solution, however simple numerical approaches can be adopted to solve the problem.

We now study the relation between the node density and the optimal transmission range. Let λ^* be the solution of the optimisation problem:

$$\lambda^* = \mathrm{argmin}_\lambda \{\mathrm{Cost}(\lambda)\} \ . \tag{7.11}$$

In Figure 7.8 we show λ^* as function of δ. We notice that for very low node densities, the model suggests a strategy that prefers to repeat many short range transmission, i.e., it relies on redundant transmissions to deliver a packet. The optimal transmission power has a maximum around $\delta = 0.006$ but then it decreases again since the nodes are so dense that the protocol can achieve good performance with low energy. The fact that λ^* is not a monotonic function of the node densities does not mean that the protocol cannot take advantage when we move from $\delta = 0.002$ to 0.05 as shown by Figures 7.9 and 7.10. These two figures show the plots of the expected energy consumption and delay per meter associated with λ^*. We observe that, as expected, higher node densities give lower costs and hence better performance.

7.6. Concluding remarks

In this chapter, we have proposed a model for an opportunistic routing protocol for UWSNs, namely DBR. Despite the assumptions done to allow for an analytical tractability of the performance indices, the model gives an insight on the impact of the parameter settings on the behaviour of the protocol. Specifically, two important performance indices have been considered: the expected energy consumption and delay for unit of distance covered by one hop transmission. Based on these performance indices, or on a combination of the two, one can optimise the most important parameter which is the transmission power. Future works include the extension of the model in order to cope with the 3D characteristic of omnidirectional antennas and to allow non homogeneous deployment of the network nodes. In the latter case, the model could be used also for determining the optimal node deployment for a homogeneous energy consumption of the nodes, and hence for a longer lifetime of the network.

8

Identifying the Optimal Transmission range in Depth-based routing for UWSNs

In most of our previous work, we concentrated on stochastic modeling of depth based routing. These works include the identification of the optimal number of hops between the source and destination nodes and, the computation of the optimal depth threshold considering network energy consumption and packet delivery ratio. In this chapter, we present a simulation study with the aim of understanding the impact of the transmission range of the nodes on the network performance indices, with particular attention to its energy efficiency. The study is based on an extensive set of simulations performed in AquaSim-NG using a library that has been developed with the aim of providing an accurate estimation of the nodes' energy consumption. The main outcome of this chapter is showing the relation between transmission range providing the optimal DBR energy efficiency and the density of the nodes in a UWSN.

8.1. Introduction

In UWSNs, the mobility of nodes makes strategies based on the identification and storing of routes hard to apply in practice. Routes are continuously broken and new ones are created [93]. DBR [24] is a localization-free routing scheme and only relies on depth information of nodes in order to transfer data from the source to the sink node. When a node transmits a packet all of its neighbors can receive it due to the broadcast nature of the considered acoustic transmission, however only the low-depth neighbors are eligible for forwarding. When a packet is sent, the protocol aims at selecting the neighbor which is nearest to the surface as forwarder so that the total number of hops is reduced and, as a consequence, the end-to-end delay and the energy consumption are also reduced. This allows the algorithm to control the flooding and reduce the probability of interference. As discussed in detail in chapter 3, the forwarder selection is based on two strategies: the first is the introduction of the depth threshold which states the depth over which a node cannot be a forwarder, while the second is the holding time, i.e., a delay whose duration is proportional to the depth difference between the sender and the candidate forwarder. Hence, when a node receives a packet that must be forwarded, it waits for the expiration of the holding time and decides to retransmit the packet only if no other node in its receiving range has previously forwarded it. DBR is considered as the pioneer and one of the most reliable schemes in the category of opportunistic routing algorithms for UWNSs and is still largely studied in the recent literature about UWSNs.

The actual deployment of a UWSN using DBR must face some design problems concerning the identification of the optimal configuration parameters for the protocol such as the constants for the computation of the holding time and the depth threshold value. However, it should be clear that also the configuration of the physical layer parameters affects the performance of the network. Specifically, the node transmission range strongly influences the energy cost of the protocol. High transmission ranges consume more energy and increase the probability of interferences but allows DBR to cover longer distances with one hop. This consideration suggests that there must exist optimal values for the transmission ranges (see [94] for an analytical model of terrestrial networks addressing this problem). Another important observation is that the optimal transmission range depends on the node density, since lower densities imply longer transmission radius in order to avoid packet losses due to the absence of eligible neighbours in the sender range.

8.2. Related work

Harris et.al [15] propose a simulation model to compute an accurate transmission power required to meet the SNR threshold of $20dB$ at the receiver for various intermediate distances among the nodes. They also devise a model for an acoustic channel and provide its comprehensive implementation in NS2 by employing passive sonar equation. We use this work for modelling the correct transmission events in our simulation model. In the literature of underwater networks, aspects of physical layer have been taken into account for improving the performance of routing and MAC protocols. To this aim, efficient localization strategies, optimal transmission range selection and design of operational modes of acoustic modems showed to be helpful in increasing the network lifetime, improving the robustness of its connectivity and decreasing the end-to-end delay.

Porto et.al [45] propose an extended form of Distance-Aware Collision Avoidance Protocol (DACAP) by augmenting it with optimized transmission power and range selection for sensor nodes. However, in contrast with DACAP, it is not necessary true for DBR that the optimal transmission range is the minimum radius that ensures the network connectivity as it will be evident from our experiments. Gao et.al [95] provide an analytical model for the evaluation of the network power consumption. Based on this model, they propose a method for obtaining the optimal transmission range for a randomly deployed network.

In [96], the authors suggest a novel routing scheme supplied with adjustable transmission range technique for sensor nodes with the aim of minimising the end-to-end delay and increasing the energy efficiency. The proposed Energy efficient Innovative Time Reduction Communication (E-ITRC) protocol exploits the relay-based communication for reducing the expected number of intermediate hops towards base station. However, E-ITRC adopt a dynamic transmission range adjustment and hence, with respect to DBR, it requires a much more sophisticated protocol implementation. Finally, they examine the impact of the transmission range on some relevant performance indices such as the energy efficiency and the network connectivity. However, only one hop transmissions have been considered and the abstraction of the analytical model makes it hard to derive a practical rule for setting the protocol parameters.

Although all of these papers aim at specifying the optimal transmission range for the combination of some MAC layers and routing protocol, still to the best of our knowledge there is no work considering DBR optimal transmission ranges by taking into account the detailed implementation of the network (e.g., busy terminal problems and so on). To cover this gap, we adopt our implementation [97] of DBR in AquaSim-NG [3] which is a NS3 based simulator and its libraries have been designed with a more efficient and detailed simulation framework for UWSNs. AquaSim-NG is an enhanced version of AquaSim [29] which is a specialized simulator for underwater networks and contains complete layered architecture.

8.3. Problem Statement

When we deploy an UWSN using DBR routing protocol, the setting of the network layer parameters, i.e., the holding time and the depth threshold, is helpful to minimize the energy consumption but may be not sufficient. In fact, the selection of an optimum transmission range at the physical layer may drastically reduce the network energy cost (and hence its lifetime) while maintaining a reasonably high packet delivery ratio. Transmission range plays a pivotal role in determining the energy consumption and the packet delivery ratio in a UWSN implementing DBR. Let us focus on the energy cost defined as the expected energy required to successfully send a packet to the sink node. Short transmission ranges cause problems in the network connectivity and hence frequently require packet retransmissions that cause a high energy consumption. On the other hand very long transmission ranges require more energy per packet and cause the increase of the number of redundant transmissions caused by hidden terminals.

In this work, we seek the optimal value of the transmission range given a certain node density that results in a low energy consumptions and maintains a reasonable high packet delivery ratio. Moreover, an appropriate choice of the transmission range reduces the busy terminal problem [63] by limiting the burden on more stressed nodes from the network traffic.

Contributions In this chapter, we address the problem of estimating the optimal transmission range for DBR based UWSNs by resorting to a detailed simulation model that takes into account a broad set of relevant aspects of actual network deployments. To this aim, we use the extension of AquaSim-NG [3] presented in chapter 4. Thanks to this development, our simulation model is able to tackle the problem of the busy terminal which is well-known to be important for the estimation of the network energy efficiency [24]. We have considered several scenarios and we have experimentally derived a relation between the optimal transmission range and the node density.

Structure of the chapter Section 8.4 briefly recalls the main features of DBR and describes our simulation model. In Section 8.5 we show the results of our simulation experiments and discuss them. Finally, Section 8.6 gives some final remarks. The work described in this chapter has been published in [98].

8.4. DBR and its simulation model

In this section we briefly recall DBR and present the main features of our simulation model. We take a bottom up approach based on the layer partition of the protocol stack. Particular attention will be devoted to the analysis of the power consumption and the loss probability at the physical layer.

8.4.1. Modelling the power consumption at the physical layer

At the physical layer, the transmission power consumption of an acoustic signal in UWSNs is computed by using the passive sonar equation presented in [15] which gives the SNR at the receiver based on some parameters among which a major role is played by the transmission power and the Attenuation-Noise (AN) factor. Notice that transmission frequency (f) dominantly affects the level of noise as higher frequency tends to increase the noise loss of signal. Moreover passive sonar equation also uses Directivity Index (DI) which shows the ability of receiver's hydrophone to avoid unwanted noise. We assume its value as 3 dB.

The transmission power required to achieve a target SNR at receiver over distance d can be computed using the algorithm (2) as follows [15]: Algorithm (2) accurately predicts

Algorithm 2: Computation of transmission power consumption

$AN[i] \leftarrow Attenuation\ Noise\ factor\ for\ ith\ frequency$
$of\ signal\ bandwidth$
$k \leftarrow Spreading\ coefficient$
$d \leftarrow Euclidean\ distance\ between\ nodes$
$Thorp(f[i]) \leftarrow attenuation\ loss\ for\ ith\ frequency$
$of\ signal\ bandwidth$
$Noise(f[i]) \leftarrow noise\ loss\ for\ ith\ frequency\ of\ signal$
$bandwidth$
$Pr \leftarrow SNR\ threshold\ of\ receiver$
$Pt \leftarrow Transmission\ power\ required\ to\ successfully$
$transmit\ signal$
$Num\_freq \leftarrow Number\ of\ frequencies\ in\ the$
$bandwidth\ of\ signal$
$DI \leftarrow Directivity\ Index$

for $i \leftarrow 0$ **to** Num_freq **do**
  AN[i] $\leftarrow -$ (k $*$ 10 $*$ $\log_{10}$(d) + d $*$ Thorp(f[i]) + DI + $\log_{10}$(Noise(f[i])));
  if $AN[i] > AN[max\_index]$ **then**
    $max\_index \leftarrow i$
  end if
end for
Pt = Pr $-$ AN[max_index];
return Pt;

the required transmission power considering various distances between the communicating nodes. By targeting specific SNR at the receiver, the passive sonar equation gives the required transmission power which majorly increases with the distance (see, e.g., [15]).

Figure 8.1 shows the transmission power required to successfully achieve the signal strength of 20 $dbre\mu Pa$ at the receiver.

8.4.2. DBR network layer and its simulation model

In DBR, nodes use pressure-based sensors to estimate their depth and rely on this information to transmit the packets to the on-surface sink. As DBR is a controlled-flooding based scheme the correct setting of its parameters, namely the *depth threshold* and the *holding time*, plays a pivotal role for obtaining high performance with a low energy consumption. Intuitively, the forwarder selection is based on the packet scheduled sending time which is decided on the basis of computation of the holding time. The packet holding time is proportional to the depth difference between the sender and the candidate forwarder and hence it favors the nodes that allow the packets to cover longer distances towards the sinks. The depth threshold is used to prevent nodes with low depth difference to become candidate forwarders. During the holding time duration, nodes discard the enqueued packet upon finding its transmission from a lower depth neighbor. DBR targets lowest depth neighbor of sender as an optimal packet forwarder which is also helpful in suppressing transmissions of other eligible neighbors of sender node. Thanks to its stateless and distributed nature, DBR is capable of handling the routing in UWSNs with high node mobility and maintains a low resource usage (there is no need to store routing

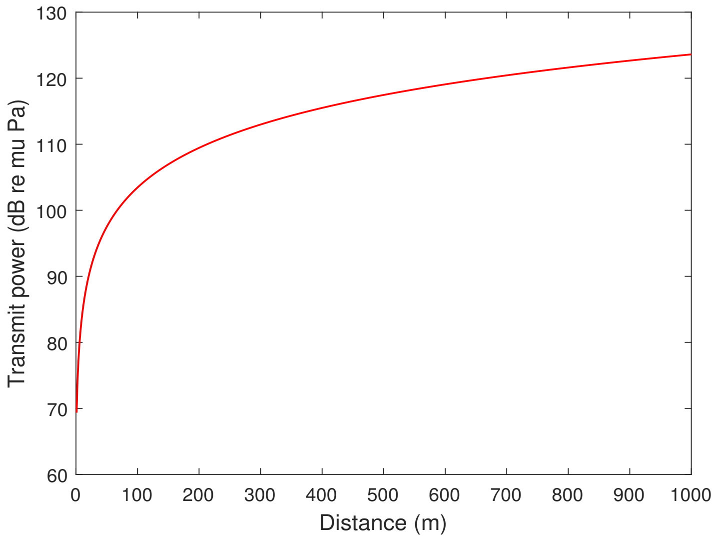

Figure 8.1.: Required transmission power for various distances

tables) and easiness of implementation.

According to [24] in DBR, the holding time is obtained as follows:

$$f_{\mathrm{DBR}}(d) = \left(\frac{2\tau}{\delta}\right) * (T - d),$$

where T is the maximal transmission range of a node, τ is the maximum propagation delay of one hop, i.e., $\tau = T/v_0$ (where v_0 is the sound propagation speed in the water), d is the depth difference between the sender and the receiver and δ is a scaling factor of the holding times which is chosen in order to achieve the optimal performance of the network and to minimize the hidden terminal problem. The analysis of the impact of these configuration parameters on the network performance has been done in [24]. Nevertheless, in this chapter we focus on the impact of a configuration parameter at the physical layer, namely the transmission range, on the network performance expressed in terms of the expected packet delivery ratio and the energy cost.

8.5. Simulation experiments

In this section, we address the problem of identifying the optimal transmission range of sensor nodes with respect to the energy cost of the network by resorting to the simulation model. We study UWSNs with various numbers of nodes deployed in a fixed space of $500m \times 500m \times 500m$ according to a uniform random distribution. The number of nodes varies from 100 to 800 and hence we recreate the scenarios that are similar to those that have been previously studied for other purposes in [24]. The depth-threshold is 1/4 of the maximum transmission range, and the mobility pattern is a random walk. For MAC layer, we implement Broadcast MAC protocol [62] which efficiently supports the functioning of flooding-based routing protocols. The source node is placed in the bottom of the network. Multiple on-surface sinks have been deployed and the source node transmits a single packet after every two seconds. Table 8.1 summarizes the experiment setting.

Together with this optimization we also study the packet delivery ratio for the optimal

Parameter	Value
Network size	500m ×500m ×500m
Deployment	Random uniform
Initial energy of nodes	500J
Packet size	64 Bytes
Node mobility speed	2 m/s
Receiving power consumption	0.1 W
Idle power consumption	1 mW
Mobility pattern	Random walk
δ	Transmission range
f	$3kHz$

Table 8.1.: Simulation Parameters

transmission ranges. The packet delivery ratio is a good measure for observing the impact of the busy terminal especially for what concerns long transmission ranges.

8.5.1. Simulation scenarios and performance indices

In order to identify the optimal transmission range, we compute the following performance indices: (i) Energy cost of network defined as the expected energy required to successfully deliver a packet measured in Joule per packet, (ii) Packet delivery ratio and (iii) Total number of transmissions of network. For each measurement we performed 20 independent experiments and build the confidence intervals at 95% whose width is always below 7% of the measured value.

8.5.2. Impact of transmission range on the energy cost of network, packet delivery ratio and total number of transmissions

In this experiment, we study the network energy cost as function of the transmission range of the sensor. Figure 8.2 shows the results of our experiments, i.e., the estimates of the energy cost of the network as a function of the transmission range for networks with 500 to 800 nodes. We observe that for very low transmission ranges the cost of retransmissions due to broken routes becomes prohibitive from the point of view of the energy consumed by the networks, whereas as the transmission range increases we have both to face the problem of the higher cost for the transmission of the single packet and the explosion of the number of retransmissions due to the hidden terminal problem and the consequent increased number of collisions. We can also observe that as the density of the nodes increases, the cost for redundant transmissions and the consequent collisions become dominant in increasing the energy cost of the network even in its optimal working point. For the four considered network densities we have an optimal transmission range of approximatively 180 meters. We will see later on that above a certain density of nodes the optimal transmission range tend to stabilize to this value under the assumptions of Table 8.1.

Consulting Figure 8.3, the packet delivery ratio quickly increases with the sharp increase in the transmission range thanks to availability of multiple paths between source node and the sinks. However, after reaching at the maximum point, it declines due to

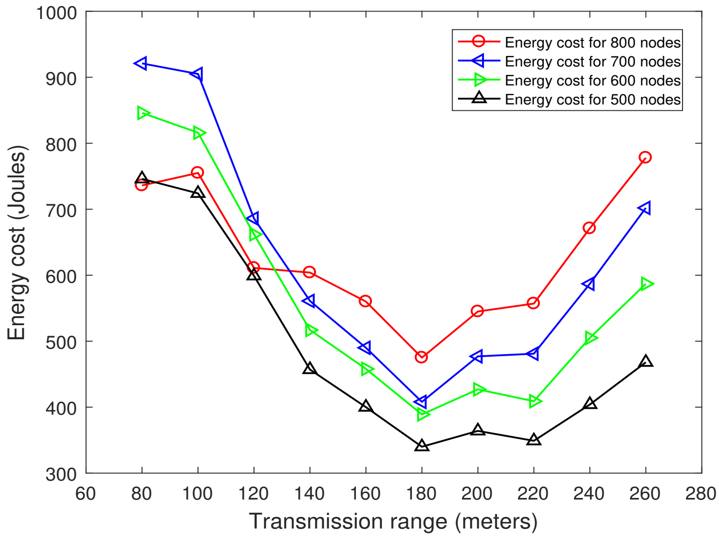

Figure 8.2.: Energy cost of the network as a function of the transmission range.

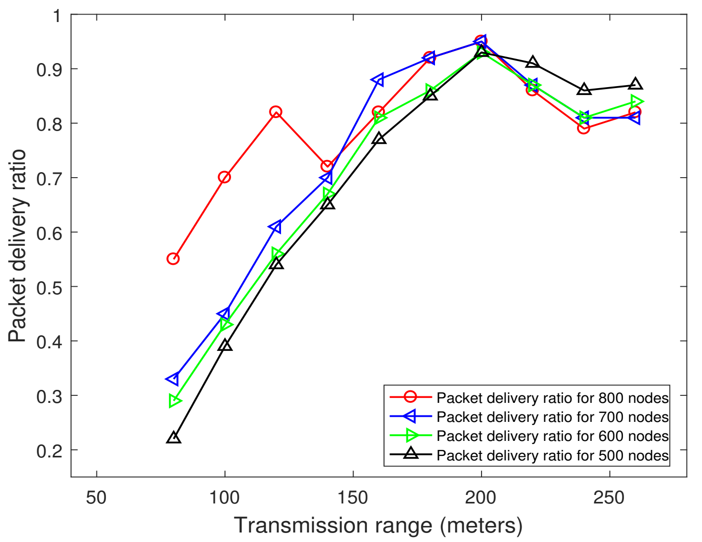

Figure 8.3.: Packet delivery ratio with different node densities.

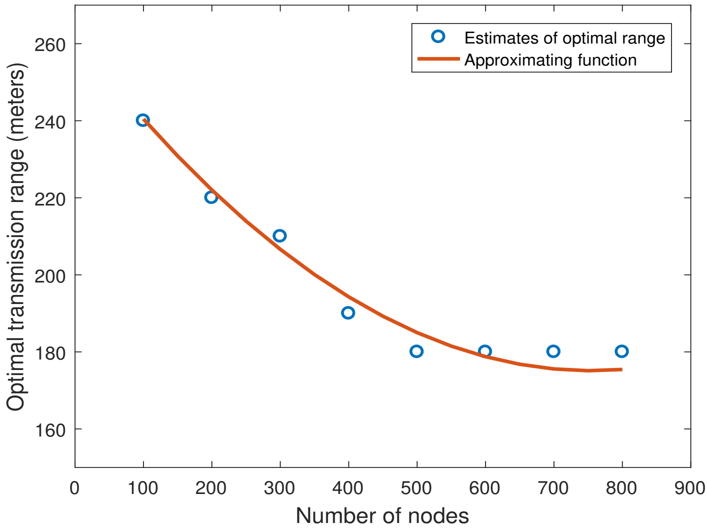

Figure 8.4.: Optimal transmission range for different node densities with minimum energy cost.

the redundant transmissions and problems caused by the busy terminals. Interestingly, the transmission range associated with the optimal packet delivery ratio is coherent with the value which optimize the energy cost.

It is also worth of notice that as observed in [63] there is a strong correlation between high packet delivery ratio and reduction of the busy terminal problem. It is worthwhile of notice that the packet delivery ratios decrease after reaching the maximum but appear to become more stable. Also for what concerns the optimal packet delivery ratio, the experiments suggest that the networks with density of 500 nodes outperform those with higher densities in case of transmission ranges longer than 200 and this may suggest that finding the optimal densities could be an interesting problem for future works. Nevertheless, we should observe that a network with high node density tends to be more robust to failures and hence other performance indices should be analyzed before drawing conclusions.

8.5.3. Optimal transmission range as function of the node density

In order to experimentally study the connection between the optimal transmission range and the network node density, we have run a large set of simulations for each given density and identified the optimal value for the energy cost. This has been done by assuming the convexity of the function $E_c = f(r)$, where E_c is the energy cost as function of the transmission radius r. Then, we have proceeded by using a bisection method. Figure 8.4 shows the optimal transmission range for various numbers of deployed nodes. We observe that for networks with a number of nodes higher than 500 the optimal transmission range stabilizes at approximately 180 meters. As observed in Section 8.5.2, this value optimizes both the network energy cost and its packet delivery ratio. As the number of deployed nodes decreases, the optimal transmission range increases to 240 meters associated with 100 nodes as number of intermediate forwarders decreases causing the decrease in total energy consumption of network.

According to our experiments if ρ is the network node density expressed in expected number of nodes for km^3, we can say that the optimal transmission range r^* for DBR decreases with higher ρ as:

$$r^* \propto \rho^{1/6} .$$

In Figure 8.4 we plot the function $745/\rho^{1/6}$ and we can see that it provides a good approximation of the estimates of the optimal range. We observe that this result is quite different from the empiric law proposed in [45] for DACAP where the optimal transmission range was found to decrease with β as $1/\sqrt{\beta}$ where β is the 2-dimensional node density.

8.6. Concluding remarks

In this work we have studied the impact of the configuration of the nodes' physical layer parameters on the performance of DBR routing protocol. In order to reach our goal, a new simulator based on AquaSim-NG has been developed that with respect to its predecessors provides an accurate modelling of the modem operational modes, the cross-layer interactions required by this protocol and the busy terminal problem. The simulator can be downloaded at the official repository of AquaSim-NG [97]. Specifically, we have addressed the problem of determining the optimal transmission range providing the lowest energy cost given the network density. To this aim we first studied the behavior of the energy cost as a function of the transmission range for networks with given node densities and empirically verified that this optimal value exists. Then, we have looked for this optimum value for different node densities. Finally, we studied the relation between the network density and the optimal transmission range. As expected, we found that sparse networks require higher optimal transmission ranges, but that this values tends to decrease slowly with denser networks.

In particular, we have focused our attention to three performance indices: the network energy cost defined as the amount of energy spent by the network to successfully deliver a packet, the packet delivery ratio and the total number of transmissions in a simulation period of $200s$. We observed that, according to our experiments, the transmission ranges that minimize the energy costs are also those that maximize the packet delivery ratio. From the experiments that we run, we observed that the optimal transmission range decreases as $1/\rho^{1/6}$ where ρ is the expected number of nodes for km^3. Future works include the development of an analytical model to validate this empirical law.

We believe that the outcomes of this work, combined with the previously developed optimizations at the network layer studied in [24], can be helpful in the optimization of the power consumption in UWSNs adopting DBR routing protocol.

9

Residual energy-Depth (RD) based routing scheme for UWSNs

In UWSNs, the localization-free routing schemes assume that nodes have no information about their location, with the exception of their depth which can be measured by a pressure sensor. In DBR, nodes broadcast their packets but only the neighbours with a lower depth than the sender are eligible for their forwarding towards an on-surface sink. Following the lines of DBR, we propose a novel and completely distributed routing protocol, named Residual energy-Depth based routing (RD). It takes into account the residual energy at the nodes' batteries to select the forwarder nodes and improves the network lifetime by providing a more uniform energy consumption among them. We compare its performance with that of DBR and a receiver-based routing protocol implementing a probabilistic opportunistic forwarding scheme.

9.1. Introduction

As described in chapter 2, routing in UWSNs is a challenging problem because of the intrinsic characteristics of this class of wireless networks (long propagation delay, mobility of nodes, etc.) and because of the performance indices that must be taken into account, such as the network throughput, the packet delivery ratio and the energy cost. In particular, routing algorithms must grant a low energy cost in order to maximise the lifetime of the network's nodes.

Among the works that consider the enrgy problem, Energy-Efficient Cooperative Opportunistic Routing Protocol [28] proposes an improved relay based routing scheme in which fuzzy logic has been employed for the forwarder set selection. The implementation has been done in NS2 based AquaSim [29]. Another recent work, Energy-efficient routing protocol [68] aims to improve the network throughput as it considers transmission collision probability as a factor to identify the path between the source and the sink node. In order to communicate the data related to packet collisions, large network overhead is required which is not always feasible. In [67], Li et al. propose a cross-layer MAC scheme, named DBR-MAC, which has been specifically designed for DBR routing protocol. It devises the adaptive depth-based backoff algorithm which assists the nodes to minimize their backoff time in case of getting empty channel for transmission. DBR-MAC minimizes the collision probability therefore it increases the network throughput.

Some of the ideas used to develop opportunistic protocols for UWSNs are inspired by the previous works on vehicular networks. In this work we consider a protocol named vehicular distributed routing which employs a probability based holding time for the relaying nodes. In [35] the authors study the trade-off between the network end-to-end delay and the throughput. The optimal relaying strategy is also proposed while considering the freeway mobility model for the nodes. Once adapted to the underwater networks, we refer to this protocol as PDBR.

Considering delay-sensitive applications of UWSN, Hsu et al. [99] propose a routing protocol in which they define opportunistic routing as a non-linear optimization model. They devise a heuristic which consists of two phases, namely the forwarder set selection and the packet forwarding prioritization. The proposed model minimizes the end-to end delay of the network. Depth-based underwater opportunistic routing (DUOR) [100] aims to solve the problem of extremely long paths and void holes during data forwarding. DUOR prioritizes the hop count parameter in order to avoid lengthy path towards sink node which in turn improves the network lifetime. Link quality-aware queue-based spectral clustering routing protocol [32] minimizes the path loss by using a dynamic clustering approach. Clusters are created on the basis of minimum signal to noise ratio between the communicating nodes furthermore, cluster head collects the data and forwards it to the sink.

9.2. Contributions

In this section we emphasise the contributions of our work.

1. We present a novel routing protocol named Residual energy-Depth (RD) based scheme. In this scheme, mechanism for the holding time computation is based both on depth and residual energy information at the nodes. Simulations show that it exhibits an improved expected network lifetime and a higher packet delivery ratio than DBR and Probabilistic DBR (PDBR) on the cost of a small increase in the overall expected energy consumption. Intuitively, RD scheme overcomes the main problem of DBR, i.e., the fact it tends to choose always the same path to the sink nodes. Clearly, by choosing alternative paths, RD scheme consumes more energy however the traffic is better balanced on the network and hence the life expectation (i.e., the average time to the disconnection of the nodes due to complete battery consumption of some nodes) of the overall system is increased.

2. We show also a deep analysis of the impact of DBR, PDBR and RD configuration parameters on the UWSN performance based on simulation experiments carried out with the tool that we propose.

Structure of the chapter The chapter is structured as follows. Section 9.3 introduces the RD-based computation of the holding time. In section 9.4, we discuss the impact of the configuration parameters of DBR, PDBR and RD on the performance indices by means of simulations. Section 9.5 concludes the chapter and discusses some future work. The work presented in this chapter has been published in [50].

9.3. RD-based routing scheme

In this section, we define the RD-based routing scheme. In RD, nodes take into account of their own residual energy and depth information in order to take routing decisions in a distributed fashion.

RD-based routing scheme combines two factors for computing the holding time: the **(i)** Nodes' depth and **(ii)** Nodes' residual energy. In contrast with the previous energy-based routing scheme of EEDBR[46], we maintain a receiver-based routing approach which is easier to implement and more robust to node movements that the sender based one. Nodes don't need to formulate complex neighbour tables which are hard to maintain due to continuous node mobility, moreover, it also minimizes the network overhead, which is required to keep in touch with location of neighboring nodes. Informally, the RD protocol tends to optimise the end-to-end delay and the throughput when the nodes' batteries are storing a good amount of energy. However, as the energy is consumed (e.g., in the busy terminals) the protocol privileges the choice of sub-optimal routes in order to improve the load balancing of the network and hence its life expectation. In practice, nodes compute their holding time by using both their own residual energy and the depth difference with the sender.

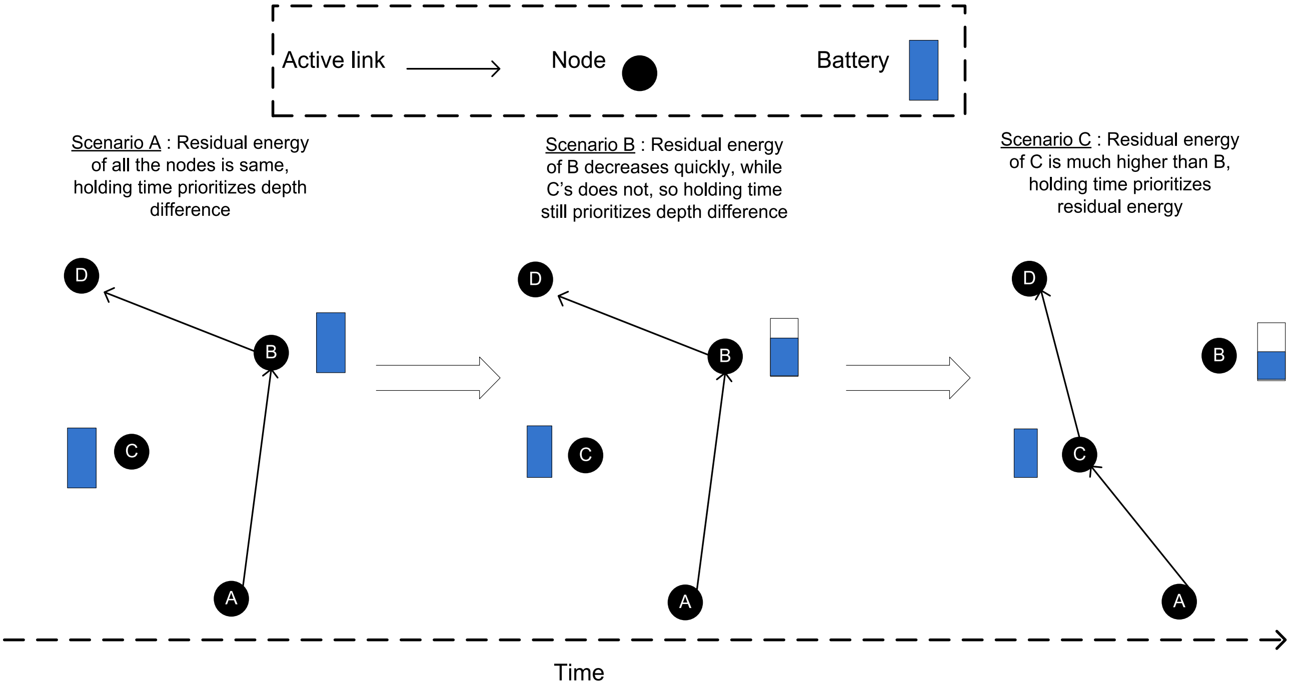

Figure 9.1.: Trend shift in computation of holding time in RD-based scheme

As a consequence, in contrast with other energy aware routing protocols [46], the format of the sent packets is identical to that of the original DBR. Figure 9.1 demonstrates the variation in forwarder selection criteria which is caused due to computation of holding time.

9.3.1. Forwarder selection

As the network initiates, our scheme follows the forwarder selection procedure prioritized by depth information of nodes considering their full residual energy. During holding time computation, it is implemented due to the higher value of $arccot(r_0/r)$ than the respective value of $arctan\ (r_0/r)$.

The forwarders are mainly selected on the basis of depth difference due to the prioritized first part. When the residual energy of the low-depth nodes is decreased due to continuous re-selection as forwarders, we enhance the impact of the residual energy of nodes on their holding time. At that moment, higher value of $arctan\ (r_0/r)$ than the respective value of $arccot(r_0/r)$ assists in selecting the high residual energy nodes as optimal forwarders.

Computation of holding time of nodes

The main formula has two parts **(i)** First part takes into account the depth difference and **(ii)** Second part employs the residual energy of the nodes. The holding time is computed as follows:

$$f_{\mathrm{RD}}(d,r) = \frac{4}{\pi}\left[\operatorname{arccot}\left(\frac{r}{r_0}\right)*\left(\frac{2\tau}{\delta}\right)*(T-d)+arctan\left(\frac{r}{r_0}\right)*max\_holding\_time*\left(1-\left(\frac{r}{r_0}\right)^2\right)\right] \tag{9.1}$$

where r the residual energy at the node and r_0 is its initial energy. $arctan$ and $arccot$ are used to set the weight of depth and residual energy in the computation of the holding time.

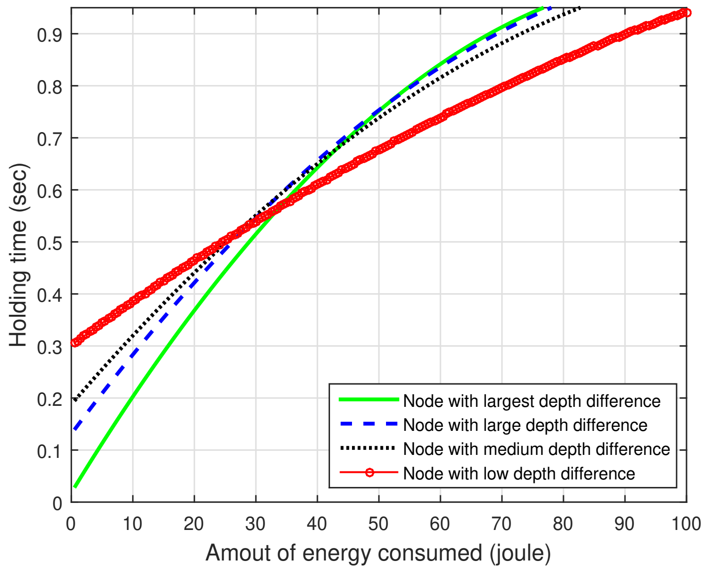

Figure 9.2.: Variation in holding time of four nodes with random depth for RD-based scheme

T is the transmission range of a node and d is the depth difference. The multiplicative constant $4/\pi$ is used so that the optimal values for τ and δ are the same of DBR when the node is fully charged. *max_holding_time* is a system parameter (i.e., the maximum holding time a node can hold a packet) and is equal to one second. τ is the maximum propagation delay of one hop, i.e., $\tau = T/v_0$ (where v_0 is the sound propagation speed in the water) and δ is a scaling factor of the holding times, which is chosen in order to achieve the optimal performance of the network and to minimise the hidden terminal problem.

Notice that as r/r_0 is close to 1, the first term of the sum in Equation (9.1) is preponderant and hence the protocol behaves by taking into account only the depth difference to compute the holding time. However, as r/r_0 is close to 0 the value of f_{RD} mainly depends on the value of the second term and hence an energy saving policy is adopted. In Figure 9.2, we consider the computed holding time of four nodes with a different depth difference with the same sender node. Initially, we assume the sharp decrease in energy of nodes with large depth difference as compared to the nodes with less depth difference.

9.3.2. Specific features

Overall, RD routing scheme is a completely distributed, receiver based scheme and hence easy to implement in actual UWSN. It relieves conventional depth based routing from the formation of complex neighbor tables which are hard to maintain due to the movement of the nodes.

In the next section, we will show that this mechanism improves the balance of the energy consumption among the nodes and hence we observe a longer lifetime of the network with respect to DBR and PDBR. However, the choice of sub-optimal paths slightly reduce the network throughput and increase the end-to-end delay when some the network nodes have low energy.

Parameter	Value
Network size	250m ×250m ×250m
Deployment	Random uniform
Initial energy of nodes	50J
Packet size	64 Bytes
Transmission Range	75m
Node mobility speed	1 m/s, 3 m/s
Transmission power consumption	2 W
Receiving power consumption	0.1 W
Idle power consumption	1 mW
Mobility pattern	Random walk
f	$3kHz$

Table 9.1.: Simulation Parameters

9.4. Simulation experiments

In the experiments, we compare the performance of the proposed RD-based scheme with that of DBR and PDBR [35] in terms of expected network lifetime, end-to-end delay, packet delivery ratio and total energy consumption of network. Under the various network settings, i.e., different node mobility speed and several values of δ. We observe that RD-based scheme improves the network lifetime while maintaining a reasonable high packet delivery ratio with the little trade-off for network energy consumption.

9.4.1. Simulated scenarios and methodology

Network nodes are deployed randomly with uniform spatial distribution, the sink is placed on the surface of the water and the source node is placed at the highest depth and at a random position with all the other nodes moving with the speed of 1m/s or 3m/s, according to the experiment. The source node transmits one packet after every 2 seconds with a packet size of 64 bytes. Other details of the simulation settings are present in table 9.1. Notice that these settings are coherent with those proposed in [24].

9.4.2. Comparison of RD, DBR and PDBR

In this section, we investigate the changes in the behavior of some important performance metrics due to various node mobility speeds. According to [24] we study our model for node speeds ranging from $1m/s$ to $3m/s$.

Table 9.2 shows the improvement in network lifetime (i.e., the time epoch at which we observe the first complete battery consumption of a node) of the RD protocol as compared to the previous schemes. The computation of the holding time in RD-based scheme provides a global load balance among the nodes, however the differences between the schemes diminishes as the node speed increases. This is because when the nodes have high mobility speeds, the problem of DBR and PDBR of selecting the same paths with high probability diminishes.

Figure 9.3 and Figure 9.4 show the packet delivery ratio for scenarios with different node mobility speeds. The packet delivery ratio for scenarios having node mobility of

Node mobility	1m/s				3m/s			
Number of nodes	100	150	200	250	100	150	200	250
RD	1090	830	806	787	1222	950	901	918
PDBR	890	731	652	639	1362	861	757	692
DBR	708	599	567	619	948	693	620	681

Table 9.2.: Expected expiration time of the energy of first node in units of time for DBR, PDBR and RD

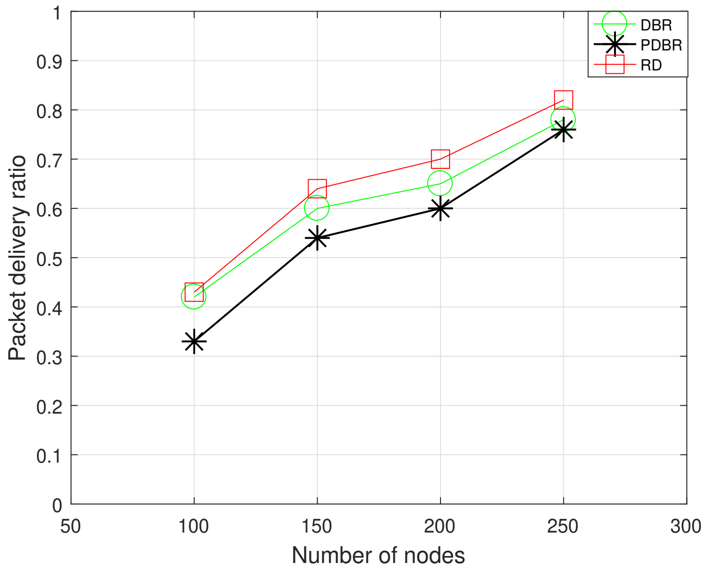

Figure 9.3.: Comparison of delivery ratio with node mobility speed = 1m/s for DBR, PDBR and RD

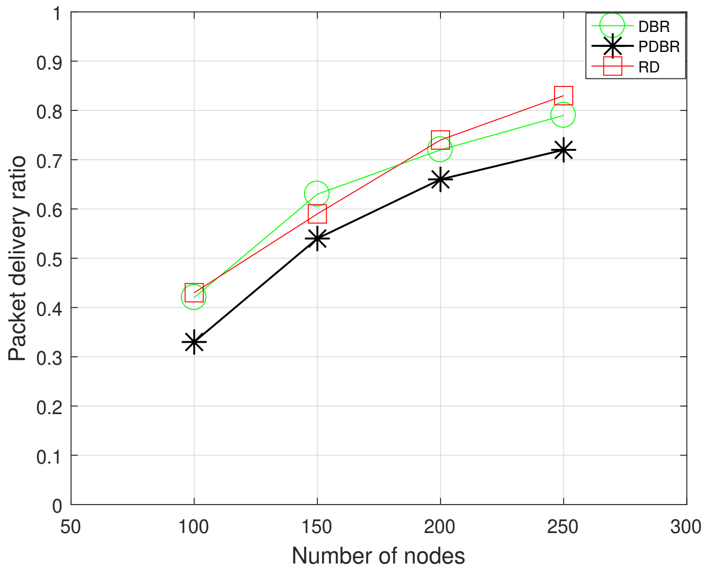

Figure 9.4.: Comparison of delivery ratio with node mobility speed = 3m/s for DBR, PDBR and RD

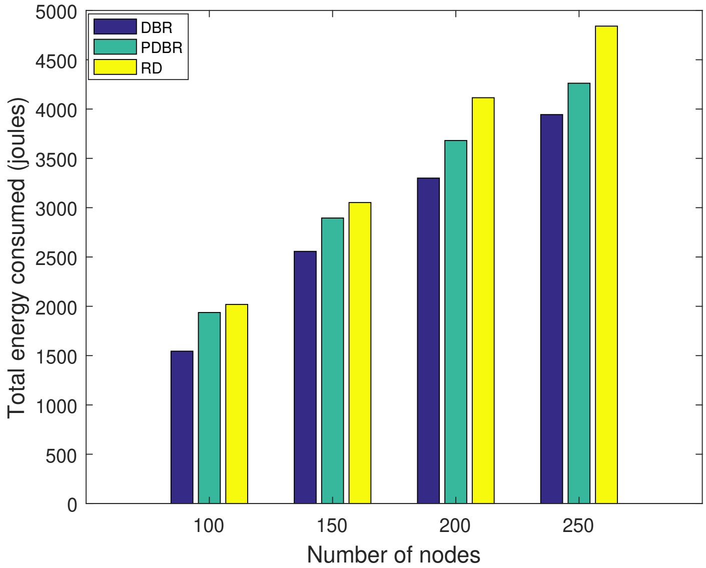

Figure 9.5.: Comparison of energy consumption with node mobility speed = 1m/s for DBR, PDBR and RD

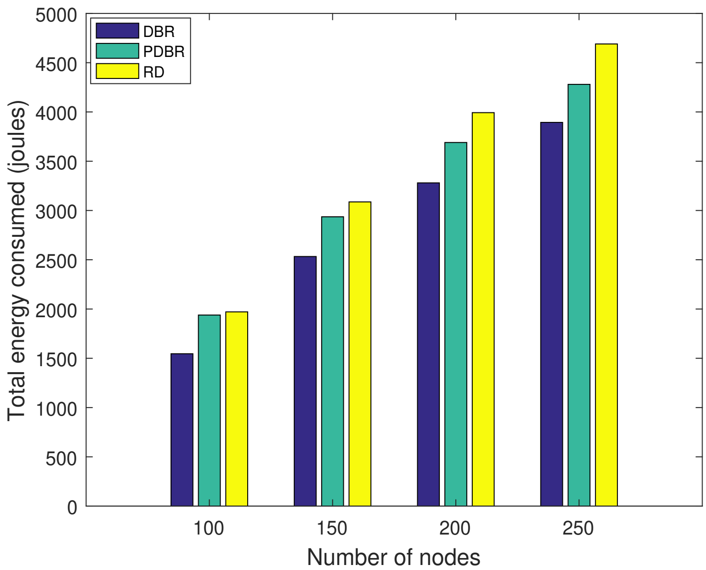

Figure 9.6.: Comparison of energy consumption with node mobility speed = 3m/s for DBR, PDBR and RD

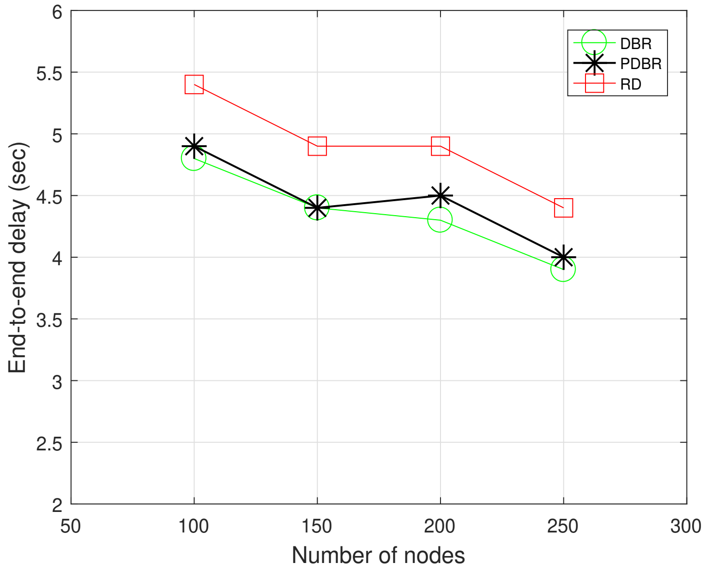

Figure 9.7.: Comparison of end-to-end delay with node mobility speed = 1m/s for DBR, PDBR and RD

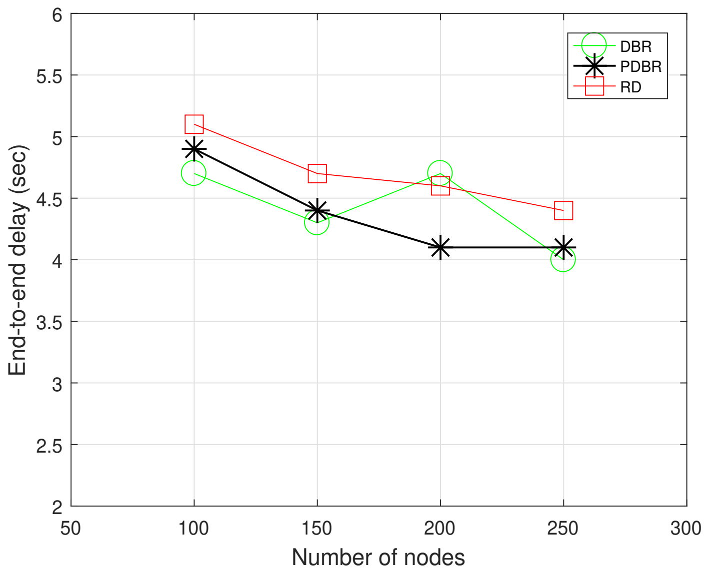

Figure 9.8.: Comparison of end-to-end delay with node mobility speed = 3m/s for DBR, PDBR and RD

Value of δ	R/2				R			
Number of nodes	100	150	200	250	100	150	200	250
RD	741	652	660	702	737	628	623	679
PDBR	664	574	502	544	596	503	488	606
DBR	574	505	472	546	508	461	469	596

Table 9.3.: Expiration time of energy of first node in units of time with various value of δ for DBR, PDBR and RD

$1m/s$ is lower than that of $3m/s$ due to a less eligible number of forwarding nodes. We see that delivery ratio increases gradually with the increased number of deployed nodes. It is interesting to observe that, coherently with [24], higher node speeds negatively affect the packet delivery ratio for sparse networks but can do the opposite effect in dense networks since the nodes tend to have a better spatial distribution. With respect to the performance of DBR and PDBR, RD-based scheme shows an increase in the packet delivery ratio as it keeps varying the selected forwarders and chooses different paths towards the sink. As a consequence, the probability of multiple available paths for the source node is increased. The lower delivery ratio of DBR is also ascribable to the fact that the nodes with lower depth are most frequently chosen as forwarders causing the network congestion and a consequent higher number of dropped packets.

PDBR also faces the issue of the lower packet delivery ratio due to the decreased number of total transmissions which is a trade-off for a reduction in the total energy consumption. Intuitively, probability based transmission in PDBR reduces the network energy consumption and gives a decreased end-to-end delay, however the packet delivery ratio is decreased.

Figure 9.5 and Figure 9.6 show the total energy consumption of the nodes in the network. We see that the total energy consumption of the DBR and PDBR is slightly lower than in RD both for node speed of $1m/s$ and $3m/s$. This is because in the RD-based scheme, there is an increment in the number of eligible forwarders which increases the number of redundant transmissions. This raises the obvious tradeoff between the increased packet delivery ratio and the total energy consumption of the network.

Figure 9.7 and Figure 9.8 show the increase in the end-to-end delay for RD-based scheme compared to DBR and PDBR. This is the consequence of the choice of RD routing to choose sub-optimal routes in order to save energy in the highly stressed nodes and hence to prolong the lifetime of the network. Another factor is that as nodes consume their energy, the holding times tend to become longer.

We also study the impact of the values chosen for the δ parameters in the performance indices. Also in these cases our experiments show a tradeoff between the packet delivery ratio and the total energy consumption. This can be observed by consulting Figure 9.9 and Figure 9.10.

Figure 9.11 and Figure 9.12 compare the amount of the energy consumed by the nodes in the network. It indicates that the scheme (i.e. RD-based scheme), in which more nodes are active in data forwarding results in high energy consumption causing local optimization as well as a global optimization for load balancing in the network. Table 9.3 shows the increase in the network lifetime of RD-based scheme as compared to DBR and PDBR, with the various values of δ parameter.

The idea is that we cannot place the burden on few low depth nodes for large amount

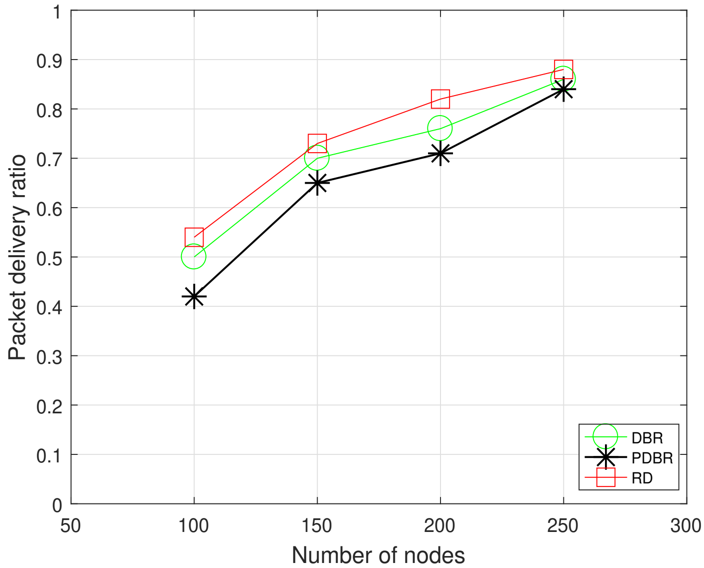

Figure 9.9.: Comparison of Delivery ratio with δ value = R/2 for DBR, PDBR and RD

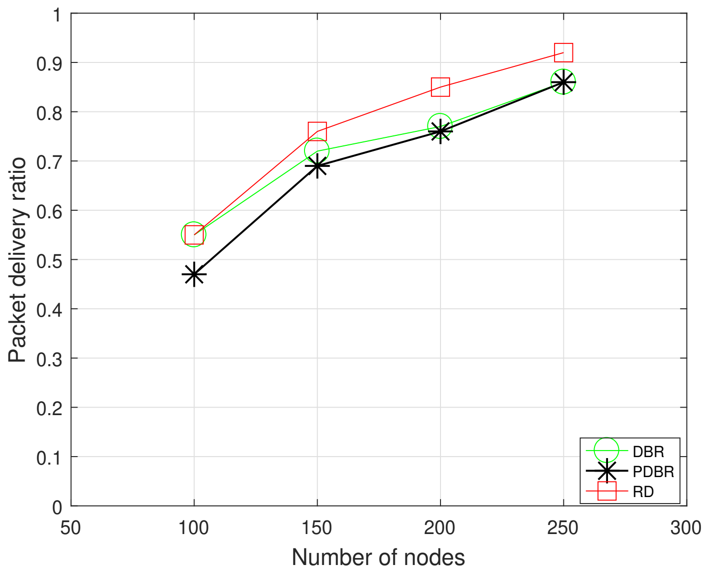

Figure 9.10.: Comparison of Delivery ratio with δ value = R for DBR, PDBR and RD

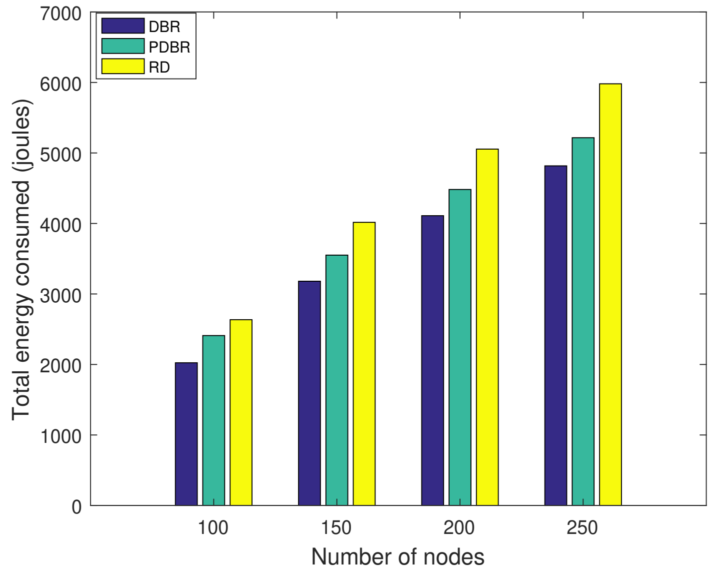

Figure 9.11.: Comparison of Energy consumption with δ value = R/2 for DBR, PDBR and RD

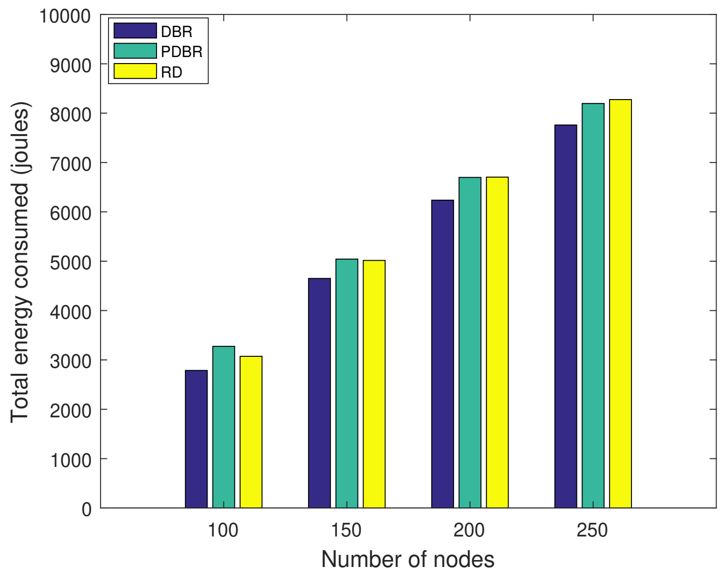

Figure 9.12.: Comparison of Energy consumption with δ value = R for DBR, PDBR and RD

of data forwarding, so in RD-based scheme, we exploit the metrics e.g. holding time computation to reach this aim. In our model, the implementation of operational modes of nodes (see chapter 4) during the running network demonstrates the importance of providing approximations of accurate sending and receiving time of packets at physical layer, as it largely affects the performance metrics. As the network becomes denser, the energy consumption increases also due to the increase in total idle power consumption. Overall, high total energy consumption seems as a tradeoff parameter for increased network lifetime and improved packet delivery ratio of network.

9.5. Concluding remarks

In this work we propose a novel routing protocol, named RD, which, in contrast with DBR, PDBR and EEDBR, maintains the characteristics of being a receiver based forwarding scheme while taking into account the residual energy of the nodes for the selection of the forwarders. Based on our tool, we have evaluated the performance indices of the RD-based scheme and the previous depth-based routing schemes. We show that this new way of computing the nodes' holding time provides a better load balancing in the network although the end-to-end delay may be increased. In fact, the main idea of RD is that we can renounce to choose the quickest route for a packet in order to reduce the busy terminal problem and to distributed the forwarding role to a larger number of nodes.

10

Adaptive Holding time and Depth-Based Routing for UWSN

In UWSNs, traditional enhancements of Depth-Based Routing (DBR) scheme rely either on increasing the network overhead or on the adoption of offline localization schemes to improve the network performance in terms of energy consumption, end-to-end delay or network throughput. Unfortunately, localization based techniques are very hard to implement in practice.

In this work we show some preliminary results about the performance of a routing scheme called Adaptive Holding time and Depth-based routing (AHT) that we propose to dynamically adapt DBR configuration parameters. Specifically, we show a set of simulation experiments that suggest that networks implementing AHT show a reduced energy consumption with respect to those implementing the standard version of DBR. Simulations are performed by using our simulation library [49] of DBR [24] developed for the simulator AquaSim-Next Generation (NG) underwater simulator, which is based on Network Simulator-3 (NS3). The characteristics of this library (detailed representation of cross-layer communications and operation modes of the modems) allows us an accurate prediction of the performance improvement of AHT with respect to standard DBR. The work presented in this chapter has been published in [101].

10.1. Background

In the recent years, UWSNs have emerged as a major research domain due to their applications for the management of seabed, pollution monitoring, seismic monitoring etc. The performance of the applications of UWSNs largely depends on the efficient utilization of acoustic signal as a transmission link. Previous works [30, 102, 103] in the domain of underwater acoustic communication can be classified according to their ISO/OSI level, e.g., physical, Medium Access Control (MAC) and network layer. Depth Based Routing protocol (DBR) is a network-layer protocol that uses some cross-layer features. One of its strengths is that it is a localisation-free routing [2] protocol, i.e., it requires only the knowledge of the depth of the nodes. Despite this limited amount of information, DBR is capable of tackling the typical challenges of UWSNs such as the node mobility and the large transmission losses. Localisation-free routing protocols work in a fully distributed manner, specifically DBR [24] capitalizes the depth information of nodes to successfully transmit data from the source node to the on-surface sink. For determining the depth information of nodes, pressure based sensors are employed.

For performance evaluation of sensor networks, various simulation environments has been proposed. During literature review, we passed through the models designed for the computation of the network energy consumption and different methods of energy harvesting in sensor networks. Erol et al. [85] provide the model to study the phenomenon of energy packet networks and discuss the relation between the energy flow and data packet transmission. In [104], authors propose an algebraic framework to predict the network connectivity and communication interference in mobile-adhoc networks. Node mobility has been taken into account in order to perform the behavioral analysis for wireless networks. In another work, Bujari et al. [105] propose an analytical model to analyze the well-known congestion avoidance mechanisms in large-scale networks, in which they have evaluated the performance of the mechanisms through various metrics e.g. average queue length, expected queuing time and system throughput etc.

10.2. Problem motivation and contribution

DBR considers the depth difference between the sender and the receiver node for the selection of the forwarder. The main mechanism adopted by DBR is rather simple: when a node receives a packet, it computes the depth difference between itself and the sender. If this value is below the depth threshold, then the packet is discarded. Otherwise, the node waits for a time (called holding time) which is proportional to the depth difference. In this way, nodes that are closer to the surface are more likely selected to be forwarders.

In this context, we have to set two parameters: the depth threshold and the multiplicative factor for the computation of the holding time. Lower values of these parameters increase the total number of transmissions in the network and hence the expected energy consumption for successfully delivered packet, whereas larger values reduce the packet delivery ratio and the end-to-end packet delay. Moreover, it can be seen from previous works that the optimal value for these parameters strongly depend on the node density of the network. In this work, we propose AHT, a technique that allows nodes to dynamically estimate the node density in the region of the UWSNs where they lay and adapt their configuration parameters in order to achieve a higher network efficiency. The protocol shows its benefits in networks where the nodes are distributed in a non-homogeneous way.

10.3. System model

We consider a 3D network providing the nodes deployed with the uniform random distribution. On the physical layer of acoustic communication, we employ Thorp's formula [15] in order to compute the total attenuation of acoustic signal as follows:

$$10logA(l,f) = k * 10log(l) + l * 10log(\alpha(f)), \tag{10.1}$$

In the above equation, l denotes the Euclidean distance between the sender and receiver, f is the frequency of the signal, k is the spreading coefficient while $\alpha(f)$ shows the total absorption loss of signal. We estimate the total noise loss NL by combining the four components below:

$$NL = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)\,. \tag{10.2}$$

where $(N_w(f))$ denotes the wind factor, $(N_s(f))$ is the shipping factor, $(N_{th}(f))$ is the thermal factor and the $(N_t(f))$ is the turbulence factor. We use the BroadcastMac [62] protocol for the medium access control.

In our network, the total end-to-end delay is composed of multiple components. The holding time delay of nodes and the propagation delays are the two major components. Speed of the acoustic signal is denoted by q which can be computed as follows [56]:

$$q = 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 + (1.333 - 0.126t + 0.009t^2)(S - 35) + 16.3z + 0.18z^2, \tag{10.3}$$

$$t = T/10. \tag{10.4}$$

where T is the temperature in $^\circ C$, S is salinity and z is the depth in km.

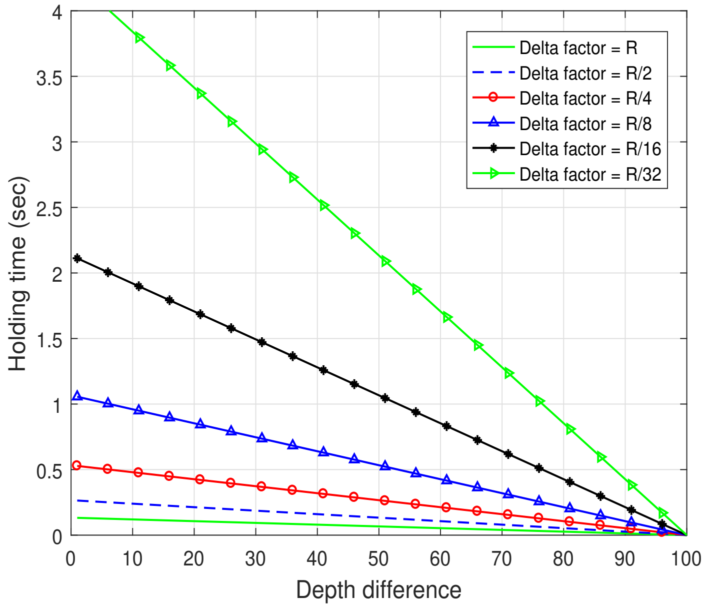

Figure 10.1.: Variation in duration of holding time due to changes in delta factor for AHT

10.4. Methodology of AHT

The protocol operation has been separated into the sequential parts. First of all, nodes receive the packets from all the neighbors and check the stored depth information of the neighbors in the header of the received packets. Nodes start to count the number of their low-depth neighbours along with averaging their depth differences. Then, starting from the high depth region, all the nodes transmit their computed δ factor and the neighbour count in the packet header, which is ultimately used by receivers to decide about data forwarding.

Adaptive holding time computation In this work, we follow the receiver-based approach of DBR with the following modifications:

- Nodes compute an estimate of the number of their lower depth neighbors (N) by checking the depth information stored in the packets received from them up to a certain time. N is then further added to the header of the packets sent by the node.
- The receiver uses the received value of N to compute their own δ factor and then the holding time for the received packet.

The holding time is computed on the basis of the formula given below:

$$Holding\_time(d, N) = \left(\frac{2\tau}{\delta}\right) * (T - d) \text{ , where } \delta = T/N \tag{10.5}$$

where N is the estimated number of lower-depth neighbours of the sender node, τ is a maximum propagation delay for direct communication in the network, d is the depth difference between sender and receiver, and T is the maximum transmission range of any node. In our scheme, δ depends on the value of N thanks to which the receiver is able to estimate the neighbor density around itself during the competition for the packet

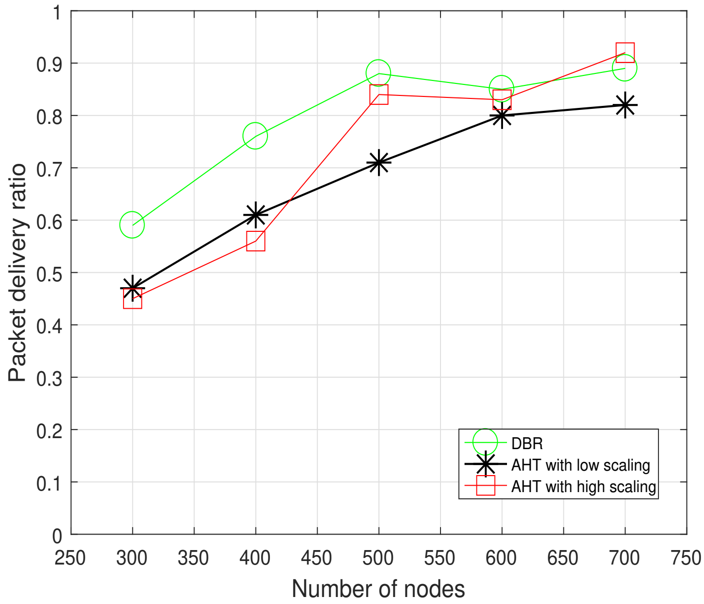

Figure 10.2.: Packet delivery ratio of network for various number of deployed nodes for DBR and AHT

forwarding. If N is high, this implies a high neighbor density around itself, and hence this results in low value δ factor as well as a large scaling of the holding time for the received packet.

Due to the large scaling of the holding time, redundant transmissions by the hidden terminals are reduced. As a consequence, this leads to a decrease in total network energy consumption and an increase of the network lifetime. On the contrary, low values of N results in the low scaling of the holding time and the fast re-transmission.

Average-based Depth threshold We also propose the adoption of an average-based depth threshold (AD_{th}) which is determined by computing the average of depth differences between a sender node and its lower depth neighbors. Instead of using a fixed depth threshold as in DBR, receiver nodes find their eligibility for data forwarding by using the AD_{th} stored by the sender node. Formally, AD_{th} is computed as follows:

$$AD_{th} = \left(\sum_{i=1}^{N} d_i \right) / N \text{ , where } AD_{th} > D_{min} \tag{10.6}$$

D_{min} is the minimum limit for AD_{th} to avoid the flooding, whereas d_i is the depth difference of sender and ith receiver node. Each node computes the respective AD_{th} for its receivers by averaging their depth differences and stores this information in the header of transmitted packets. The information is used by a receiver to find its eligibility for data forwarding. In case of high neighbor density, this mechanism further decreases the number of total transmissions in the network due to increase in AD_{th} while it maintains the high packet delivery ratio.

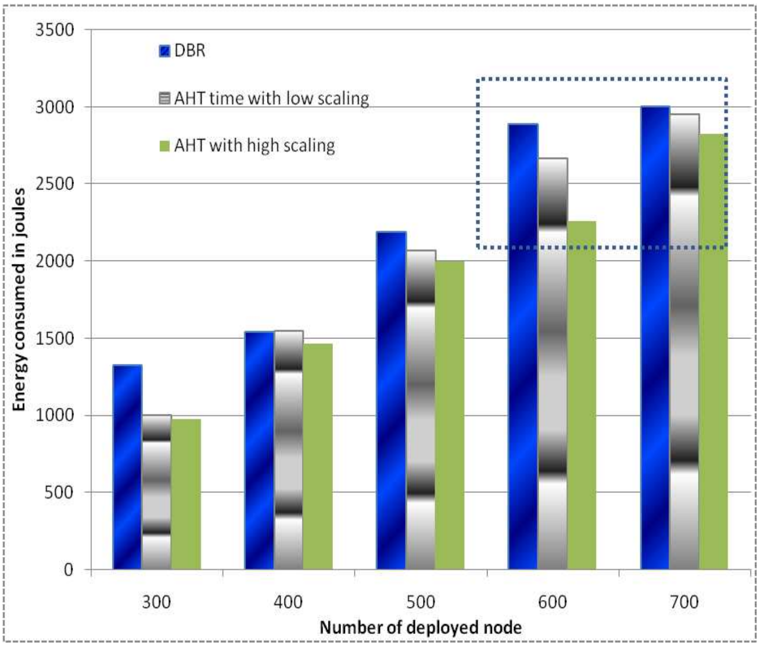

Figure 10.3.: Total network energy consumption for various number of deployed nodes for DBR and AHT

10.5. Results and discussion

Simulation have been performed in underwater specialized simulator AquaSim-NG [3]. In our simulation settings, we took a network of size 500m ×500m ×500m adding that the number of deployed node varies from 300 to 700.

For our initial results, we took fixed transmission range and no mobility for nodes. We compared our results with DBR and computed the important performance metrics of total energy consumption, end-to-end delay and packet delivery ratio of the network. In Figure 10.3, we show that the total energy consumption decreases for high network density scenario which is also providing maximum packet delivery ratio. However, for less number of deployed nodes, there is a little improvement as it results due to minimized hidden terminals in lower network density. The end-to-end delay is the trade-off parameter which is increased due to high scaling of δ factor. Figure 10.2 shows that although the packet delivery ratio of our scheme is lower than of DBR for less number of deployed nodes, however, it is ignored as the optimal number of deployed nodes are preferred by which maximum packet delivery ratio could be achieved. Therefore, our scheme performs much better for the dense conditions. Figure 10.4 demonstrates that the end-to-end delay for high scaled δ factor is higher than the other two schemes which acts as a trade-off factor to minimize energy consumption of the network.

10.6. Concluding remarks

In the domain of localization-free routing protocols, most novel routing protocols ignore the basic rules of design which make them a little bit unrealistic. These protocols usually employ offline localization schemes which increase the energy efficiency of the network, however increase the network deployment cost. We devise AHT routing protocol, which

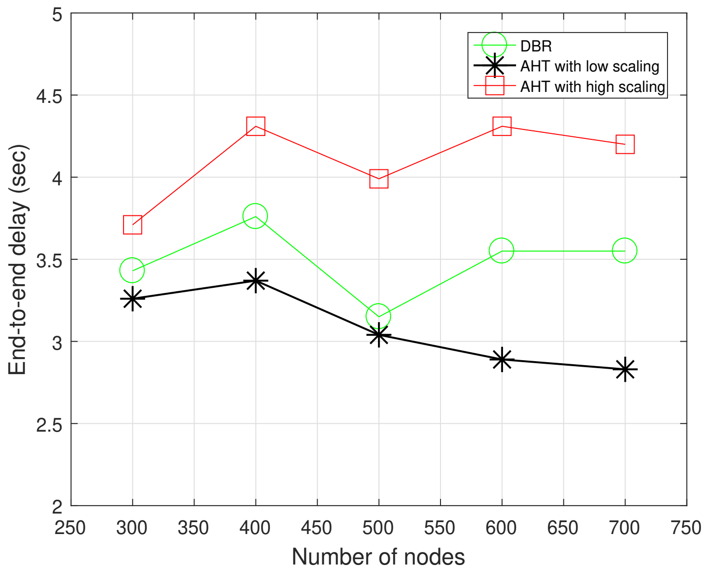

Figure 10.4.: End-to-end delay of network for various number of deployed nodes for DBR and AHT

decreases the total energy consumption of the network at the cost of end–to-end delay specifically for the highly dense networks. We provide its multiple versions by discussing the high scaling and low scaling cases of the δ factor. In the future work, we aim to tackle the mobility issues of our scheme.

11

Conclusion

In this thesis, we have presented our work in the field of analysis and simulation of routing protocols for underwater sensor networks (UWSNs). UWSNs employ sensor nodes to detect physical attributes of water such as temperature, pressure, etc. In the recent years, UWSNs have been emerged brilliantly for their applications such as management of the oil reservoirs, exploration of the deep sea situation and prevention of aqueous disasters. Overall, we have contributed to the development of the field by implementing a new simulation tool for underwater networks, and by devising some new stochastic models that allow for a better understanding of the dynamics of underwater routing protocols, specifically for what concerns their performance thanks to these results we have been able to propose guidelines and algorithms for determining the optimal parameterisation of routing protocols for UWSNs. Particular attention has been devoted to a crucial aspect that determine the actual implementation of a routing strategy, i.e., the energy consumption.

In order to design the simulator, we studied the state of the art of the simulation tools for UWSNs with particular attention to those based on the Network Simulator (NS). We also explored the literature review for UWSNs, acoustic communication, further moved towards the Underwater Acoustic Sensor Networks (UASNs). In chapter 4, we developed a new tool based on NS3, which extends the previous Aquasim-NG in order to encompass a detailed model of the energy consumption of underwater sensors. Specifically, the accurate implementation of the operational modes of acoustic modems and of the underwater channel loss models make this tool a valuable instrument for the performance evaluation of UWSNs. We analysed the flow of packets at different layers of networks under various network conditions in order to validate the results of our model. We also studied an abstraction of an opportunistic routing protocol and derived its optimal working conditions based on the network characteristics. Our simulator tool is available for free and distributed as open source [49].

Routing protocols in UWSNs propose different methods for data routing towards surface sink or sonobuoys. The dynamic conditions of water, variations in topologies, energy constraints and high error probability during data forwarding are prominent challenges in the design of routing protocols in UWSNs. Moving towards the routing protocol design for UWSNs, we analysed and optimised depth-based routing (DBR). DBR is one of the main distributed, receiver-based protocols employed for routing in UWSNs. DBR devises a robust opportunistic forwarding mechanism that efficiently handles channel errors.

In chapter 5 and chapter 6, we discuss our collaborative research works with Prof. Dieter Fiems and Prof. Majid Ghaderi, respectively. In chapter 5, we developed a stochastic model to find the optimal number of forwarding hops between source and destination that minimized the energy consumption while maintaining reasonable goodput and end-to-end delay. In this model, node mobility plays the central role moreover, the model allows the analysis of the impact of mobility on some relevant performance indices, including the packet delivery ratio and the energy consumption. From the practical point of view, the result allows the network designer to choose a proper parameterisation given the mobility patterns of the nodes. In chapter 6, we designed an accurate probabilistic model of a general opportunistic routing scheme that allowed us to study the impact of the depth threshold in the definition of these types of protocols [79]. In practice, in this work, we proved that the optimality of opportunistic protocols can be reached by introducing a threshold on the eligible forwarders of a packet. Moreover, the work gives a computational method for deriving this threshold and studies the trade-off between packet delivery ratio and expected number of forwarders for each transmission. We also show that there is a critical depth threshold above which the probability of a correct packet transmission to the surface sinks drops drastically and hence the network communications turn out to be unfeasible. This further highlights the importance of properly configuring the routing protocol. All these conclusions have been validated thanks to the simulator that we developed in the first part of the thesis.

Despite its simple formulation, the correct functioning of DBR depends on a set of configuration parameters whose values are not easy to estimate by using stochastic simulation. Although DBR is widely adopted for actual UWSN implementations, in the literature there are very few models for its analysis, and hence finding the optimal parameter sets is a hard task. In our next two works, we worked to partially cover this gap by proposing a set of analytical models that allows the efficient computation of the performance indices of networks employing DBR. In chapter 7, we proposed a technique to parameterise the protocol configuration that depends on the local conditions of each node, in particular on the number of perceived neighbours [78]. Simulations show that the solution helps in controlling the energy consumption of the network. In chapter 8, the model that we propose aims at determining the optimal transmission power for DBR networks by studying the trade-off between the energy consumed for a certain transmission range and the number of retransmissions required to reach the sink [98]. We discuss the implications of our results and validate them by means of stochastic simulations on AquaSim-NG.

In chapter 9 and chapter 10, we proposed two novel distributed opportunistic routing protocols thanks to the considerations and experience developed in the first part of the thesis. In chapter 9, we proposed the novel receiver-based routing scheme Residual energy-Depth (RD) based protocol in which we improve the network lifetime [50]. In chapter 10, we proposed a novel routing scheme called Adaptive holding time based routing (AHT), which reduces the energy consumption with respect to DBR [101]. We exploited the parameters of depth threshold and scaling factor for the holding times which are the main deciding factors in optimising routing performance.

Future work includes the need to design a localisation scheme for underwater nodes in order to improve the performance of the AHT routing algorithm. In fact, AHT is useful for static node deployment in UWSNs however, its performance drops down for the high node mobility as the nodes loose the count of expected number of low-depth neighbors. This issue can be solved by using localisation scheme capable of predicting the expected number of low-depth neighbors for any node by inferring some properties on the mobility patterns of the nodes. These patterns can be deduced by monitoring the signal strengths and by adopting some stochastic mobility models. Therefore, the analytical results proposed in this thesis can be exploited to obtain the optimal configuration parameters of the routing protocols given the state of the network portion that interacts with a certain node.

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