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A CROSS LAYER PROTOCOL FOR A NON-SYNCHRONOUS LOCALIZATION SCHEME IN LARGE-SCALE UWSNS (UNDERWATER WIRELESS SENSOR NETWORK)

Presented in 02 February 2022 :

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Notations

ACK	Acknowledgment
AE2ED	Average End to End Delay
ALOHA	System for a multiple access to a shared communication Networks channel
ALOHA-AN ALOHA	with Acoustic Networks
ALOHA-CS ALOHA	with Carrier Sense
AOA	Angle of Arrival
Aqua-Sim	Aqua Simulator
ARQ	Automatic Repeat reQuest
AUV	Autonomous Underwater Vehicle
CDMA	Code Division Multiple Access
CH	Cluster Head
CLMD	Cross-Layer Mobile Data
CLSD	Cross-layer Protocol Stack Development
CPU	Central Process Unit
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
DBR	Depth Based Routing protocol
DD-UT	Drift Dependent Underwater Tracking
DESP	Distributed Estimation of Sensor Position
DHL	Dual-Hydrophone Localization method
DSSS	A Dynamic Slot Scheduling Strategy
EC	Energy Consumption
EE	Energy Efficiency
EEMR	Energy Efficient Multi-path Routing Protocol
EKF	Extended Kalman Filter
FDMA	Frequency Division Multiple Access
FP	Forwarder Position
GPS	Global Positioning System
H-MAC	Hybrid Medium Access Control
HSR-TDMA	Hybrid Spatial Reuse Time Division Multiple Access
ID	Identifier
JTSL	Joint Time Synchronization and Localization Design for Mobile node
LMB	Localization with a Mobile Beacon
LRF	Localization and Routing Framework
LSL	Large Scale Localization
MAC	Medium Access Control
MBS	Mobile Beacon and Sink
MEES	Mobile Energy Efficient Square
NADIR	Network Aware aDaptive Routing Protocol
NAM	Network Animator

NCHARQ	A Network Coding Based Hybrid ARQ
NCRP	Novel Cross-Layer Routing Protocol
NEFP	Novel Efficient Forwarding Protocol
NS-2	Network Simulator 2
OP	Source Position
ORML	Orthogonal Regression Based Multi-hop localization
OTcl	Object-oriented Tool Command Language
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PLAN	Protocol for Long-latency Access Networks
P-MAC	Preamble Medium Access Control
POCA-CMAMAC	A Path Oriented Code Assignment CDMA-based MAC protocol
PSD	Power Spectral Density
QELAR	Q-learning-based Energy-efficient and Lifetime-aware Routing protocol
QoS	Quality of Service
RCAMAC	Reservation Channel Acoustic Media Access Protocol
RF	Radio Frequency
RF-EM	Radio Frequency Electromagnetic
RLS	Reverse Localization Scheme
R-MAC	Reservation Medium Access Control
ROV	Remotely Operative Vehicle
RSSI	Received Signal Strength Indicator
RTS	Request To Send
Slotted FAMA	Slotted Floor Acquisition Multiple Access
SNR	Signal to Noise Ratio
TCL	Tool Command Language
TCP/IP	Transmission Control Protocol Internet Protocol
TDMA	Time Division Multiple Access
TDOA	Time Difference of Arrival
T-Lohi	Tone Lohi "Lohi means slow in hawaiian"
T-MAC	Timeout Medium Access Control
TOA	Time of Arrival
TP	Target Position
TSL	Time Synchronization Free Localization scheme
UDP	User Datagram Protocol
UKF	Unscented Kalman Filter
UPS	Underwater Pressure Sensor
UWAN-MAC	Underwater Wireless Acoustic Networks Medium Access Control
UW-MAC	Underwater Medium Access Control
UW-OFDMAC	Underwater Orthogonal FDMA MAC
UWSN	Underwater Wireless Sensor Network
VBF	Vector-Based Forwarding Routing Protocol
VBVA	Vector Based Void Avoidance
VP	Priority Value
WPS	Wide Coverage Positioning System
WSN	Wireless Sensor Network

Introduction and thesis overview

Since the technology is being developed continuously day by day, the need to access and share information at any location by the human beings have become frequent, whereas the wired networks are not suitable to afford such a possibility, hence the development of a new technology which does not require any of infrastructure or wires have taken place those last centuries, those technologies includes the Wireless Sensor Networks (WSN), which are equipment with the ability to operate without infrastructure setting up.

The Wireless Sensor Network refers to a set of multiple sensor node relying to each other through a wireless link, that has the ability to record and store physical conditions of a certain environment and communicate it to a base station. As the WSN have become an enabling technologies for the scientific researchers, and are used for several purposes, those technologies have been divided into multiple categories, according to their scope of use and their deployment environment, we can cite : the Terrestrial WSN, used only for terrestrial context as for security measurement (monitoring or military context), medical applying (exploring the human body), environmental (natural disaster or event), or even home automation (Household devices), Underground WSN which are used for earthquake prevention in most of time, WSN Multimedia, sensors that can store, processed and retrieves multimedia data such as: (video, image, sound), Mobile WSN, sensors with the ability to move in a certain environment and can be used for many applications such as vehicular sensor networks, and the Underwater WSN : sensors or vehicles deployed in a marine environment that are frequently used for sea monitoring, aqueous environment exploration, and disaster prevention.

Despite the numerous benefits that the Underwater Wireless Sensor Network (UWSN) are providing to the scientific community in different application field, those technologies are confronted to several challenges that can significantly affect their performances due to the unpredictable conditions of the marine environment, the limitations of UWSN are mainly their insufficient bandwidth and energy constraints, their high signal absorption due to the use of the acoustic support, and their frequent change of position, hence numerous studies and researches have been evaluated and established included the routing protocol that have for purpose to guarantee the communication and the achievement of information to the right destination, in UWSN technologies, once an information is recording by a sensor node it has to be sent to a certain source, named SINK, meanwhile the other sensors located between the two stations and collaboratively communicating this information to the sink through multi-hop communication model, those types of routing protocol are limited for the reason that the path over the next sensor node is not defined, sensors have only the ability to discover other sensors that are relying to it one hop previous and one hop next neighbors, besides that the interruption of a link between two sensors due to their mobility or their energy depletion, can harshly affect the network performance.

The main goal of this thesis is to enhance the well-known protocol (Vector Based Forwarding routing protocol VBF) which is designed for Underwater communication, since VBF presents certain limits and challenges. Our main contribution is aimed to improve the protocol in a cross-layer manner, a technique that consist the operation of the two layer of the TCP/IP model, Network layer and the Medium Access Control layer (MAC).

Motivation and contribution
Our studies were been focused on future link failure or interruption between two communicated sensor nodes for multiple reasons that will be described and illustrated latterly.

In our first contribution, we have proposed a new mechanism for an earlier link interruption detection and preemption, using the Lagrange Interpolation formula, for a future link quality estimation through the MAC layer, the main purpose of this study was to avoid unnecessary packet transmission due to weak link quality caused by the mobility of sensors during data relaying process, and rediscover another potential sensor with which the link quality is quite effective, the method is aimed to detect and prevent from failures, and thereafter recover the information to the upper layer in order to disclaim the communication with the concerned node and launch a rediscovering process.

In our second contribution, the problem of a future link interruption caused by nodes mobility and energy depletion are the main issue, where the prediction of future link corrosion is estimated using Newton Interpolation formula, the sensors uses the link efficiency estimation before any transmission process, if the sensor is receiving a weak signal from it previous sensor, this latter will not participates in the data forwarding process, this study was implemented in a cross-layer fashion in order to retrieve more information that the MAC layer can afford to the Network layer during the data packet routing.

The third proposed study was conducted to analyze the network performance of the proposed contributions over the protocol VBF, in order to prove and evaluate the reliability of the proposed mechanisms using different network parameters, the main purpose of the comparison performance was to demonstrate the efficiency of the implemented methods, and the addition advantages that it has brings to the protocol VBF, furthermore, to clarify which is the best mechanism for the future interruption prevention is the more efficient to adopts for the underwater acoustic communications.

Thesis structure
This thesis is organized as follow :

- The first chapter presents an overview about the wireless sensor network technology, thereafter, the chapter introduce a bright explanation about the Underwater Wireless Sensor Network, by describing more details on their applications, architecture, communication support, their challenges and limitations, and their routing schemes.
- In the second chapter, different localization scheme using in the routing protocol that are based on the location information of sensors are outlined, following by a presentation of some of the routing protocol based on the localization of sensors, then the cross-layer design is introduced along with some of the realized routing protocol based on this method, thereafter, the acoustic link quality and the impact of their weaknesses and failures are initiated, then the routing protocol Vector Based Forwarding protocol (VBF) is described, and finally the implementation environment used to evaluate the proposed contributions is explained and detailed.
- The third chapter illustrates the major issues discussed in the presented contribution, where some of the related works are cited and explained, then the proposed mechanisms

conducted to overcome the addressed issues is widely detailed with the obtained results and their discussions.

- The fourth chapter introduces another major issues related to the underwater acoustic communication, where some of the proposed works are cited and briefly explained, in addition the implemented mechanism that provides an enhancement of the basic routing protocol VBF is mainly detailed and described, the obtained results are represented and discussed.
- The fifth chapter provides a comparison study of the network performance of both implemented techniques, where different parameters are used, the obtained results are summarized, discussed and explained.

At the end, a conclusion of our work is presented besides some of the future works and perspectives as well.

1 Underwater Wireless Sensor Network

Contents

Introduction

The wireless sensor networks have become a wide research area in those last recent years, for the large application coverage that it has provided to the research community and human beings [Hussein, 2014], those technologies was motivated by several application, such as military surveillance, seismic prevention, tracking and event monitoring [Swetha et al., 2018]. Since more than 66 % of the earth is covered by water, principally oceans, it become crucial for humans to explore the oceans for a future development purpose [Nazareth et Chandavarkar, 2020], however their explorations presents a great challenges for the scientific researchers due to the greatness of the oceans, the presence of a high water pressure, and predatory fish, which makes the task difficult to manage, hence the underwater wireless sensor networks have bring a large interest to the scientific community, for the various applications that it can brings for different fields, such as oceans surveillance, disaster prevention, assisted navigation, mine detection and oceanographic data collection [Hussein, 2014].

Whereas the underwater wireless sensors are confronted to multiple water issues, since the underwater devices communication are using acoustic link communication, however it presents some weaknesses as the large propagation delays, limited bandwidth and battery power, the presence of a significant noise and interference, and high bit error rates, hence several studies have been conducted recently in order to support the acoustic communication and overcome the present issues in the marine environment [Rahman, 2017], while the technologies are still confronted to many challenges.

In this chapter, a basic concepts of the wireless sensor network is presented, then the underwater wireless sensor networks are detailed and depicted with their different application, their used architecture, communication support and their challenges, in addition, although the most implemented routing and medium access layer protocols used for the wireless networks are not suitable and appropriate for the underwater environment, several algorithms have been suggested and designed for the acoustic communication, hence this chapter include as well the different technique and classification used for the MAC protocols and routing protocols along with the issues and challenges which represents the routing in the underwater acoustic communication.

1.1 Wireless Sensor Network

A wireless sensor network are composed of multiple devices that are equipped with a processor, a radio transceiver including antenna, an analog-to-digital converter, sensors, memory, and a power supply [Rawat et al., 2014], those sensor nodes are dispersed and spatially distributes in a certain environment in a random way and are connected to each other over a wireless connection, forming a network topology [De Gante et al., 2014] using radio communication waves according to the Figure 1.1. WSN are able to sense and record event such as physical conditions from the environment where they are deployed, organize and transmit the event sensed in the form of a data packet from a source sensor to a destination sensor [Gupta et Sinha, 2014]. The collected data is relaying through multiple sensors, and collaboratively communicated to a station called Sink [Rawat et al., 2014], thereafter the information is sent by the sink to a gateway sensor, where the gateway has the ability to communicate this information to the outside environment that can includes (Internet, Users...etc). Wireless sensor network became one of the common promising technologies and are being deployed for diverse applications, and offering supplies advantages over the conventional networking solutions as lower costs, scalability and reliability, flexibility, and their ease deployment that allow their utilization in a large range of different application [Rawat et al., 2014].

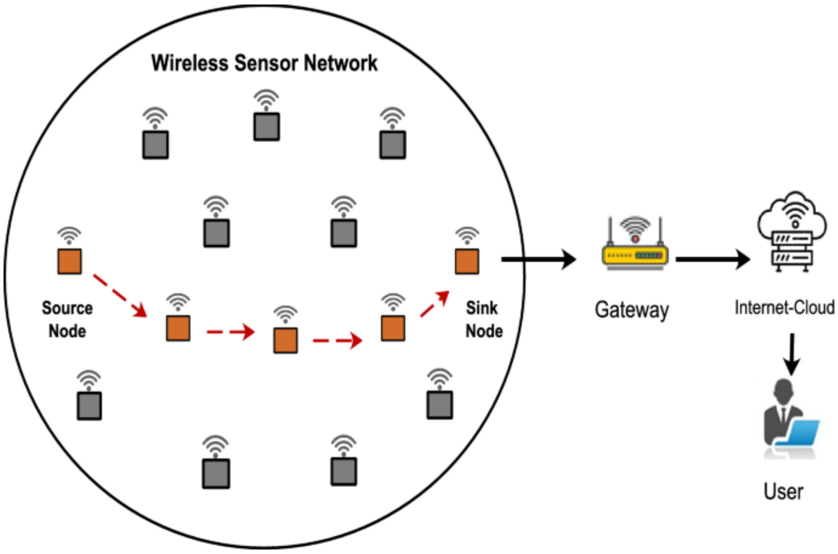

Figure 1.1 – *Wireless Sensor Network [Jaiswal et Anand, 2020].*

1.1.1 WSN Application

WSN technologies have been use for military context (surveillance and monitoring) in the past, but since, their applications have been extended for multiple purposes and uses [Singh et al., 2016].

- **Disaster prevention :** WSN are used for natural disaster prevention, according to the area where they are placed, they are enable to sense and measure the earth's physical conditions, and anticipating a future natural disaster (earthquakes, landslides, air pollution...etc) [Benkhelifa et al., 2014].
- **Medical :** for medical use, WSN are called bio-sensors which are used for healthcare, they can be placed inside a human body, they are aimed to collect information from the body, as to prevent from cardiovascular decease, cancer detection, glucose level and blood pressure monitoring [Neves et al., 2008].
- **Military environment :** where the mobile nodes can be soldiers, tanks, or fighter planes. For military applications, the wireless sensors can be used to monitor the movement of the enemy in a given geographic area, or to collect data in a dangerous area [Naimi, 2015]
- **Vehicular Network :** where individuals are presented in vehicular form containing wireless devices used for road security purpose, where they are connected to each other and able to collect, process and communicates information with other vehicles, or devices [Paul et al., 2012].
- **Smart home :** in these last decade, many household equipment can contain a wireless devices, for a light control applications [Mohamaddoust et al., 2011], window, door open and close, fire detection, video doorbell and many others, a smart home system provides safety and secure living [Ransing et Rajput, 2015], a human can control his house equipment through smart phone application, for a smart home.

1.1.2 WSN types

The WSN technology have become an important subject in researches area and have been successfully increased in the scientific communities, their application have been extended to multiple purposes according to the environment deployment.

- **Terrestrial WSN :** a set of wireless sensors deployed and placed in a geographical area, those sensors are used for multiple purposes, as security measurement for a military context or protected area monitoring, those have the ability to prevent a base station from dangerous event, moreover it can be used for environmental context as to prevent from natural disaster (earthquakes), as they can be used by household devices for home automation [Rawat et al., 2014].

- **Underground WSN :** a set of wireless sensors placed in caves or underground used for earthquake prevention in most of time, as they can be used for the measurement of underground conditions as soil composition and soil moisture, the collected events are transmitted to a base stations located in a terrestrial area [Rawat et al., 2014].

- **Multimedia WSN :** a set of wireless sensors setting up at different environment with the ability to collect, processed and retrieve a multimedia data such as: (video, image, sound..etc) through cameras and microphones equipment, they are used for multiple surveillance and tracking contexts [Rawat et al., 2014].

- **Mobile WSN :** the wireless mobile sensors have the ability to move in a certain environment where they are placed and communicates with other sensors or a base station, they can be used for many applications such as vehicular sensor networks [Rawat et al., 2014].

- **Underwater WSN :** underwater sensors are placed in water environment, where they can be autonomous vehicles (sensors with the ability to move) or fixed at a certain depth, they are frequently used for many contexts, as water conditions monitoring, and disaster prevention (tsunami prediction) [Rawat et al., 2014].

1.1.3 WSN limitations

As the many advantages that can the WSN brings to the scientific researchers, those technologies are confronted to multiple limitations and constraints :

- **Limited energy :** due to the frequent operation of the WSN during their sensing process and the information relaying, high amount of energy can be consumed, and their battery level can be easily exhausted which are not easy to replace or recharge [Singh et al., 2016].

- **Limited storage :** as the WSN are sensitive to network attack, they require high security mechanism to ensure the data authenticity that claims a good quite size of memory, the limitation of the sensor storage could make the security mechanism implementation hard [Singh et al., 2016].

- **Security limitation :** since the wireless technology is more sensitive to attack, and although the use of the Radio waves by the WSN can allow the attackers easily intercepting or injecting messages [Kavitha et Sridharan, 2010].

- **Connectivity loss :** the network topology can be harshly affected by the sensor nodes mobility, due to their frequent position change, the connectivity between sensors can be interrupted at any time that makes the network performance worsening, although sensor node can easily die due to it limited energy [Rajendra Prasad et al., 2020].

- **Radio Frequency interference :** Interference, and data packet collision are more prone to occur due to the use of RF medium, WSN suffer from hidden sensor node phenomenon, where the neighbors are using the communication support simultaneously [Watteyne et al., 2007].

1.2 Underwater Wireless Sensor Network (UWSN)

UWSN are a set of wireless sensor devices deployed and spatially dispersed, at different depth in a marine environment [Bhambri et Swaroop, 2014], they are related to each other over a wireless communication support forming a wireless network, those devices are supporting wireless acoustic communication and are equipped with antennas that have the ability to sense and measure several water characteristics [Jouhari et al., 2019], the sensed event are processed and recorded by the sensor and communicated to the other sensors. UW sensors are applying and widely use for various underwater monitoring and exploration applications, [Goyal et al., 2019]. UWSN is a newly emerging wireless sensor that is used to provide methods and mechanism to discover aqueous environment, where humans are unable to directly explore [Khalid et al., 2017], those are receiving a lot of attention and interests recently due to their advanced abilities within the ocean monitoring and surveillance, and underwater targets detecting and diverse range of application [Fattah et al., 2020].

The Figure 1.2 presents an overview of the Underwater Wireless Sensor Network design.

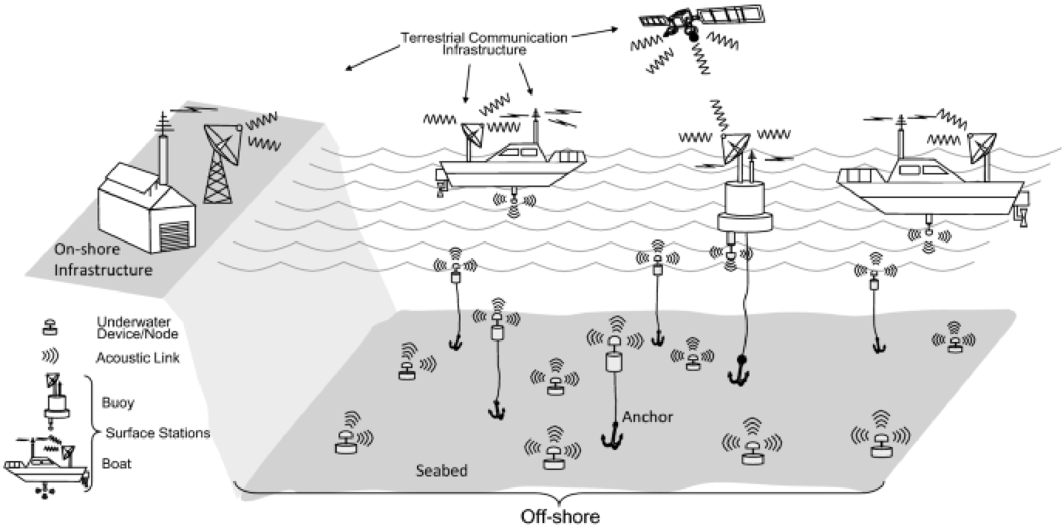

Figure 1.2 – *Underwater Wireless Sensor Network Design [Bouk et al., 2016].*

1.2.1 UWSN Operation

According to the figure 1.3 Underwater devices are related and connected to each other, in order to communicate and exchange the sensed event by a source node, the data is relaying through multiple sensors, till it achieve the right destination. The source node is generally located at the sea bed [Jouhari et al., 2019], the destination node named as sink node is located above the water surface, and the rest of the sensors are randomly dispersed. When the source node has a data to send to the sink it will flood the processed data to it sensor neighbors, the other underwater sensors collaboratively communicate the information, in a multi hop communication model [Rawat et al., 2014]. Once the data reaches the sink, this one has the ability to convert the signal from acoustic to radio in order to communicate the information to a basic station located at the earth, a satellite, or another station laid in a surface buoy [Khalid et al., 2017], UWSN are adapted to provide different services and transferring data wirelessly to the users [Fattah et al., 2020]. the Figure demonstrates the explanation above.

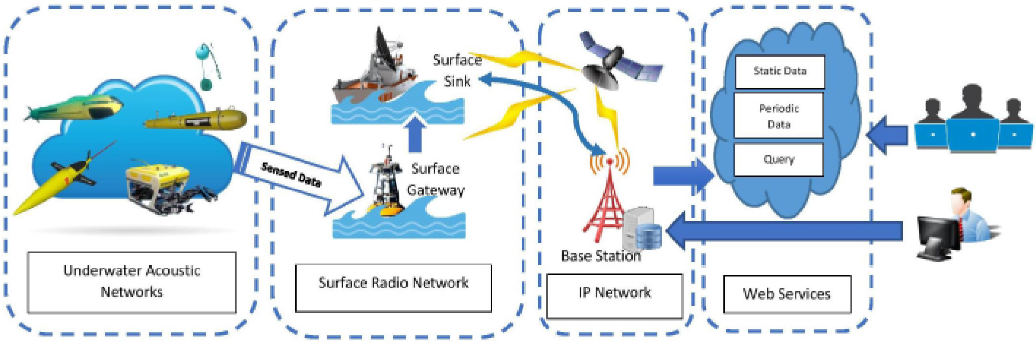

Figure 1.3 – *Underwater Wireless Sensor Network Operation [Fattah et al., 2020].*

1.2.2 UWSN Internal architecture

Underwater sensor is composed of a main controller CPU, acoustic modem, sensor interface circuitry, power supply and a memory. The controller is related to the sensor interface circuitry, that receives data from the sensor, stores it within the memory, process it and send it to other sensors, by controlling the acoustic model. The components are generally protected by bottom-mounted instrument frames, from oceans disturbance, UW sensor can measure many water conditions such as temperature, acidity, salinity, chemical products, oxygen and hydrogen, and turbidity [Hussein, 2014]. The Figure 1.4 depicts the internal architecture of the Underwater sensor.

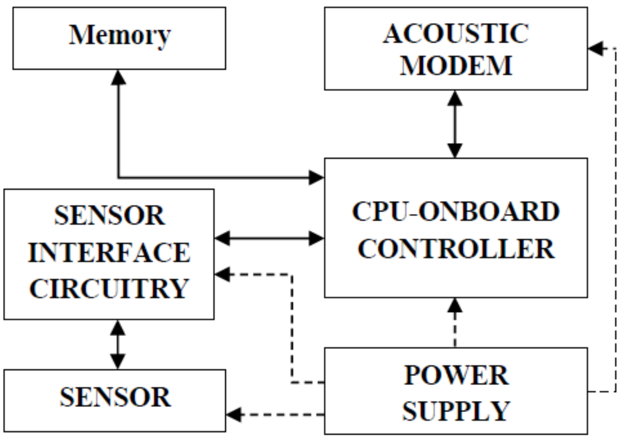

Figure 1.4 – *UWSN Internal architecture [Hussein, 2014].*

1.2.3 UWSN Elements

- **Static Sensor node :** depending on the dimensional space, in 2 Dimensional communication, static sensors are employable in deep water at the sea bed, and communicate with the sink node over multi-hop communication model, within a forming group of other sensors called cluster, while in 3 Dimensional communication, sensors are deployed according to different height, anchored at the sea bed with a wire that can be adjusted [Fattah et al., 2020]. The Figure 1.5 shows an underwater static sensor.

Figure 1.5 – *Static Sensor node [Vasilescu et al., 2005].*

- **Mobile Sensor node :** as it is shown on the Figure 1.6, the mobile sensor consists of remotely operative underwater vehicles (ROVs), or autonomous underwater vehicles (AUVs), sensors with the ability to move through the sea, owning two transceivers antenna to achieve a maximum data gathering [Fattah et al., 2020].

Remotely operative vehicle ***Autonomous underwater vehicle***

Figure 1.6 – *Mobile Sensor node [Witman, 2017].*

- **Hybrid Sensor node :** the hybrid sensor combines between mobile and static sensors, to extend the ability of the sensor in order to accomplish some operations, those sensors can be either router or controller [Fattah et al., 2020].
- **Surface buoy node :** the sensors communicate the gathered information to a surface station named sink [Zidi, 2018], which is equipped with a buoy, that can be anchored (stationary) at the sea bottom, or allowed to drift, (see Figure 1.7). The surface station owns two different types of antennas, the first one is an acoustic antenna located at the surface station bottom, that can support acoustic communication with sensors placed in the water, the second antenna support radio communication, used to transmit the received data from under water to other terrestrial station [Na et al., 2011].

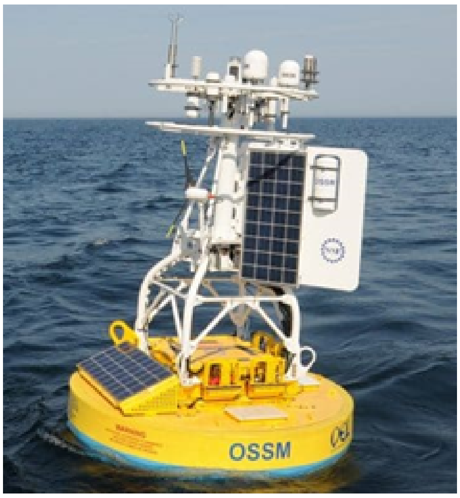

Figure 1.7 – *Surface buoy station.*

1.2.4 UWSN Architecture

The way in which the sensors are deployed in a certain area is called topology or network design it plays a crucial role in determining the energy consumption, and the reliability of a network. Developing a network with a set of sensors have to be based on an architecture to obtain a trusted network [Bhambri et Swaroop, 2014]. According to the Figure 1.8 the architecture of the underwater wireless network is classified as follow :

- **One-dimensional Architecture 1D :** The 1D architecture refers to a network where sensor nodes are processing in autonomous way, depending to them selves, the sensor can be an autonomous vehicle (AUV), that have the ability to sense, operate and moving towards the sink station to transmits the information [Felemban et al., 2015].

- **Two-dimensional Architecture 2D :** In 2D the sensors are forming multiple groups, which are called cluster, each cluster contains sensors that are anchored to the sea bed, and has one member called the cluster head, that has for purpose to collect the information sensed and gathered by the other members, the cluster head which is an anchor node uses an horizontal communication link to communicate with the sensors that belongs to it cluster, while using a vertical communication link to communicate the information to the surface station [Pompili et al., 2009].

- **Three-dimensional Architecture 3D :** Since the sensors can be deployed at different depth, the 2D architecture can no longer be suitable, a 3D architecture has been setting to support inter-cluster communication between sensors with different heights, intra-cluster communication, a sensor node with a cluster head, and anchor-buoy communication [Pompili et al., 2009, Akyildiz et al., 2004].

- **Four-dimensional Architecture 4D :** The 4D architecture combines between 3D architecture and different types of UWSN (fixed and mobile), those mobile sensors can be presented as autonomous underwater vehicles, with the ability to collect the data from the anchor node and relay it to a surface station [Felemban et al., 2015].

1.2.5 UWSN Communication

The communication in wireless sensor network means the transmission of information through different techniques, the main difference between underwater WSN and terrestrial WSN is the

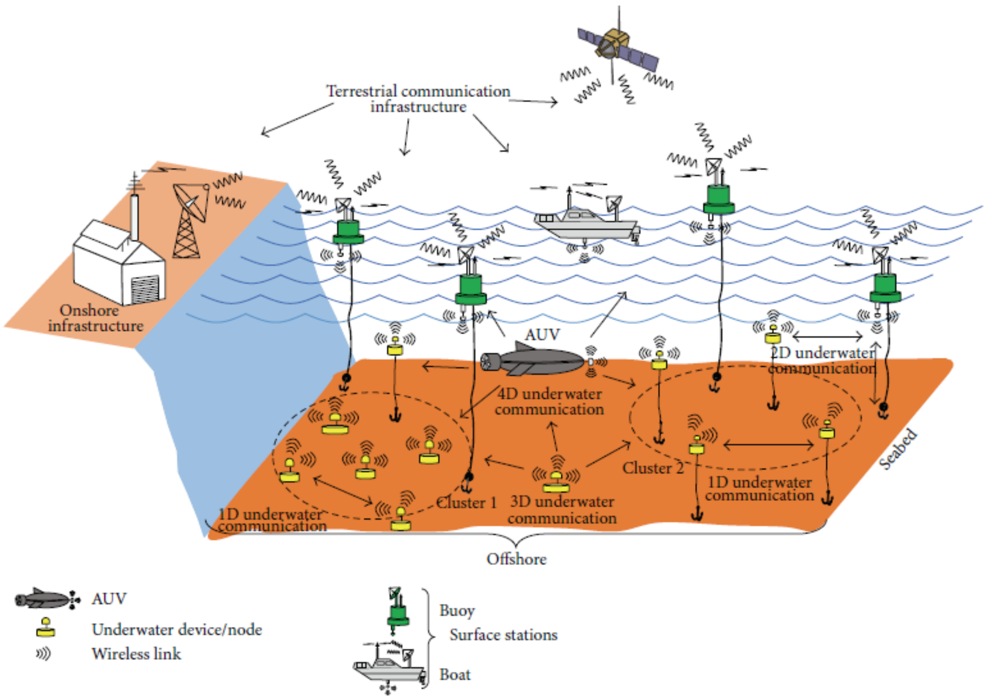

Figure 1.8 – *Underwater Wireless Sensor Network Architecture [Felemban et al., 2015].*

communication medium supported by sensors to send and transmit information. Radio signal can be used in UWSN, however the problem is that this signal propagates at long distances through sea water only at extra low frequencies between 30 Hz and 300 Hz and it requires long antenna and high transmission power which is costly. Thereafter, Optical signal can be designed as the most suitable medium but this type of signal is easily absorbs by water. In other way Acoustic signal attenuates less and travels further. Acoustic signals are the most preferred medium for UWSN. Underwater wireless sensor network communicate using an acoustic signal, when the surface station receives data from underwater sensors it will transfer it to the onshore sink or surface sink with a radio signal (RF) [Han et al., 2012, Akyildiz et al., 2005].

- **Acoustic waves :** the used of the acoustic communication waves are very common in UWSN technology and the most desirableness way to communicate in the marine environment, for the reason that the acoustic signal is less prone to be attenuate and absorbs by water unlike the Optical and RF waves, and can achieve a high distance that can cover a maximum area. Despite it advantages, acoustic waves is limited at certain points, first, as the size of the bandwidth is restricted at maximum 1 KHz, the transmission data rate is low and does not support a large size of data exchange. Second, acoustic waves suffers from high propagation delay, for the reason that the speed of the sound in water is 1500 m/s, moreover the transceivers antenna used for acoustic communication are very cost and consumes energy [El-Rabaie et al., 2015, Zeng, 2015].

- **Electromagnetic waves :** the Radio frequency electromagnetic (RF-EM) is a communication that performs at higher bandwidth and frequency that can allows a high transmission data rate, but for the fact that this signal is much more absorbed and attenuated in a marine environment, and has not the capacity to achieve a maximum range, moreover the signal is propagated at low frequencies (30-300Hz), besides the large antennas required

Table 1.1 – *UWSN communication [Kamapantula, 2011].*

	Acoustic	Electromagnetic	Optical
Speed (m/s)	1500	3.10^8	3.10^8
Bandwidth	1 kHz	1 MHz	10 - 150 MHz
Range	1 km	10 m	10 - 100 m
Power loss	>0.1 db/m/HZ	28 db/1km/100MHZ	Depends on turbidity

for it that are very cost, the RF-EM are not used for UWSN technology [El-Rabaie et al., 2015, Zeng, 2015].

- **Optic waves :** despite the advantage that an Optical communication can afford for UWSN, the High-speed transmission of the signal and the high data rate transmission, unfortunately optical signals suffers from high water absorption and scattering problem, which makes the signal not achieving a large distance, hence the Optic waves are not suitable for underwater communication [El-Rabaie et al., 2015, Zeng, 2015].

The table 1.1 resumes the capacities and the boundaries of the different communication types.

1.2.6 UWSN Application

- **Environmental monitoring :** underwater sensor networks are used for the water environmental physical conditions studies, as chemical pollution, measure some water conditions as marine current, wind monitoring, water quality and salinity, it can be applied for weather prediction and climate changes purposes [Benabdallah et Hammad, 2013].
- **Natural disaster prevention :** UWSN can be used for a natural disaster prediction, as the ocean are encountering many landslides movement, those sensors have the ability to measure seismic activities remotely and this provides tsunami warnings for coastal areas, and study the effects of sea-quakes as well [Soreide et al., 2001].
- **Military :** as the submarines are exploiting the deep oceans, they use underwater sensors to help in the ocean monitoring and surveillance for security purpose and hidden mines detection [Felemban et al., 2015].
- **Assisted navigation :** those sensors can be used to identify dangers on the water bottom, locate dangerous rocks and submerged wrecks (parts of ships destroyed as a result of an accident) [Basit et Kumar, 2015].
- **Sports :** UWSN can be applied for a sport category, in previous work [Le Sage et al., 2011], the authors presented a wireless network sensor used to monitor the performance of a swimmer or multiple swimmers. where performance is communicated simultaneously to the coach and other swimmers.

1.2.7 UWSN Challenges

As WSN have multiple limitations, and since the UWSN are deployed in a wide environment, they raise numerous challenges as well including [Awan et al., 2019] :

- **The cost :** for the reason that the UWSN are not easy to find in the commercial company besides the high quality of the devices with which they are made has to be robust against water factors, they became costly, moreover their deployment in the water environment is difficult and expensive, they requires a high maintenance and tracking regularly, which made them very costly [Akyildiz et al., 2006].

- **Battery power :** as the UWSN are depending on a limited battery that made them operational and which can not be recharged easily or replace because of their costs, and due to the frequent data collection, and sensing process by sensors, that consumes a high amount of energy, it battery power can turns off at any time, causing loss of connectivity with other sensors [Akyildiz et al., 2006].
- **Localization :** the marine current can shift the devices from their position, and affects the network topology, precisely the location of sensors which caused the inaccurate localization process, particularly if the sensors are mobile, the localization can became a great challenge for sensors [Beniwal et Singh, 2014].
- **Bandwidth :** the bandwidths in underwater sensor are limited, and depending on the frequencies using during transmission, and for the reason that acoustic signal are more prone to be absorbs in the water and it is performing under 30 KHz, bandwidths are restricted [Beniwal et Singh, 2014, Giantsis et Economides, 2011].
- **Connectivity loss :** in the marine environment sensors are more sensitive to loss the connectivity with other sensors within or outside cluster, the mobility can be the major factor of this problem from where the sensors can moves a change their position frequently, moreover the presence of interference, and the energy depletion that weaken the received signal can be the causes as well [El-Rabaie et al., 2015].
- **Propagation delay :** because of the presence of many water factors as temperature and salinity the acoustic signal tends to a high delay, this is the main reason of the high propagation delay in underwater, that is much more high than in Radio Frequency of terrestrial channels till five times slower that the propagation of electromagnetic waves [Bouk et al., 2016].
- **Noise and interference :** the acoustic channel can be confronted to many ambient noises, which can be marine animals, human activities and natural events, the water current can affect the acoustic communication as well, in addition the presence of some animals, vehicles, rocks, or boats can interfere the transmitted signal between sensors [Bouk et al., 2016, Luo et al., 2018].
- **Shadow zone :** UWSN suffers from shadow zone problem, which are zones from the network where the acoustic signal is not reachable, or it power is weak, in other studies, shadow zone are called void hole and are defined by non-existent routes to the sink [Bouk et al., 2016].

1.2.8 UWSN and TWSN differences

Due to different support transmission media and the environment deployment, the underwater sensors presents some differences from the terrestrial wireless sensor [Ayaz et al., 2011, Li et al., 2016], the following table 1.2 presents the main characteristics of both the Terrestrial WSN and Underwater WSN :

1.3 UWSN Medium Access Layer

The Medium Access Layer (MAC) of the TCP/IP model, provides a common channel access medium by multiple devices, while sharing the available bandwidth in an efficient way. (MAC) layer is aimed to ensure the reliability and the efficiency in WSN technology, by controlling the scheduling, manage the allocation of channel resources in efficient manner, and error control

Table 1.2 – *UWSN and TWSN differences*

Terrestrial WSN	Underwater WSN
Low propagation delay due to the high speed of the RF waves in air (200 000 faster than acoustic waves under water).	High propagation delay due to low speed of the acoustic waves under water (changing salinity, temperature and depth can affect the propagation speed of the acoustic waves).
Low energy consumption.	High energy is needed by the acoustic transceivers to transmit in longer distances.
High data rate due to the large frequency range normally in the order of MHz.	The acoustic waves works under water at a low frequencies from Hz to tens of KHz and due to the high acoustic waves absorption, the transmission rate can hardly exceed 100 Kbps.
Less presence of noise and interference in terrestrial environment.	Noise and interference in under water are more serious due to the presence of water current, ships, animals and reflections.
Most of the network architecture employs stationary nodes that can not move around frequently which ensures the stability of the network.	The network topology is unstable under water, due to water current sensor nodes may drift and move continuously.
Two Dimensional deployment (2D).	Three Dimensional deployment (3D).
Battery power can easily be recharged or replace.	Battery power are more difficult to be recharged or replace.
It requires dense deployment in most of time.	Sparse deployment is preferred in order cover and attempt large monitored areas.
Sensors are less error prone and can work for a longer time.	Sensors are more prone to die due to the corrosion or leave the working areas.
Less attenuation of the RF signal in air.	High attenuation and signal loss in communication due to the acoustic waves absorption in under water.

[Rahman, 2017]. Since the UWSN are suffering from additional limits, as limited bandwidth, high propagation delay, energy consumption, and dynamic topology, beside the use of the acoustic communication medium, the terrestrial MAC protocol can not adapt well for UWSN. Many last researches for MAC layer have been proposed and implemented that ensures an efficient communication for underwater wireless technology [Wei et al., 2018].

1.3.1 UWSN MAC challenges

- **Hidden and Exposed Node :** the hidden node is a problem that occurs when a station or a node can not initiates a data packet transmission for the reason that, another station using the same channel is currently sending, while the exposed node is a problem that occurs when two stations from different transmission range sends data to the same destination. The hidden and exposed node are the common issue of the contention-based collision avoidance MAC [Chen et al., 2014].

- **High Delay :** due to the control messages exchanging between stations or node manage the channel access before any data transmission, energy and time are wasting, control messages takes the most of the communication time, the high delay problem is a handshaking based MAC protocols [Chen et al., 2014].

- **Energy Consumption in Collision :** the major MAC protocols are tend to avoid collision, where two station are transmitting at same time, or two data are receiving at same time (Hidden node problem), this provides a waste of power energy [Chen et al., 2014].

- **Near-Far effect :** when the received signal by a near station is powerful than the received signal by a far station, a near-far effect problem occurs, multiple MAC protocols are aimed to adjust the transmitted signal power by a transmitter node to make the far station receive a quite enough signal [Chen et al., 2014].

1.3.2 UWSN MAC Classification

The UWSN MAC protocols have been classified into three categories as it is shown on the Figure 1.9, according to the access method or techniques :

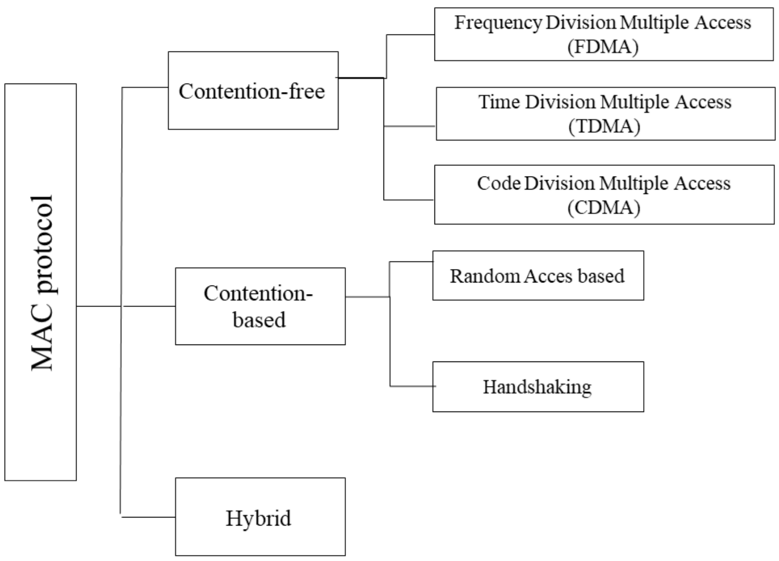

Figure 1.9 – *Classification of MAC protocol*

Contention-free MAC

The sensors use multiple techniques, depending on the method using by the MAC protocols to access the channel support, this category is subdivided based on three classes according to the access technique used

- **Frequency Division Multiple Access (FDMA) :** in this category the frequency is divided into sub frequency, where each section is allocated to one user, the channel is considered as occupied until the user liberate the support. Underwater Orthogonl FDMA MAC (UW-OFDMAC), is a MAC protocol proposed for FDMA access method, that has integrated a self-assignment algorithm to define the optimal transmission power sub-carrier spacing and guard interval duration [Chen et al., 2014, Hussein, 2014]

- **Time Division Multiple Access (TDMA) :** where the method divides a time interval into many sub times, called slots times, and allocates it to one user. A Dynamic Slot Scheduling Strategy (DSSS) has been proposed, the protocol is aimed to improve the channel utilization and prevent from collision by using four strategies, grouping, ordering decision, scheduling, and shifting [Chen et al., 2014, Hussein, 2014].

- **Code Division Multiple Access (CDMA) :** the channel users can operate concurrently over the frequency band, where the different signals are distinguished through a pseudo-noise code (PN), used to broadcast messages. A Path Oriented Code Assignment CDMA-based MAC protocol (POCA-CDMAMAC) has been proposed to allow the sink the reception of multiple packets from the neighbors, where sensors modulate their packet with a spreading sequence

Contention-based MAC

The method is designed for a random access, where many sensor nodes can use the same channel and initiate their transmissions at same time

- **Random Access based :** where data packet are transmitted in a random way, it means if a sensor node has a data to deliver it simply transmit the packet without taking any parameters into consideration, the receiver sensor can successfully receives a data packet if no other packets are arrived at this time. ALOHA protocols, are a set of MAC protocols, where a sensor has a ready data packet to transmit to a certain target sensor, it will simply send it, however collision can occurs if two sensors transmit at same time, ALOHA-CS and ALOHA-AN are some of the ALOHA protocol groups [Rahman, 2017]. Another representative class of MAC protocols called CSMA (Carrier Sense Multiple Access), where sensor has to sense the channel a certain time interval before initiating a transmission, T-Lohi and UWAN-MAC are a CSMA based MAC protocol [Chen et al., 2014].
- **Handshaking based :** handshaking is a group of reservation-based protocol, where a sender has to capture the channel before any transmission. Handshaking protocol are classified into two categories :
  1. **Single channel :** where only one channel is applied, before a sensor can transmit it will issue a Handshaking message to capture channel, Slotted Floor Acquisition Multiple Access (Slotted FAMA) has been proposed for single channel class [Rahman, 2017].
  2. **Multiple channel :** multiple channels are applied and used, where one channel is reserved for a control purpose, and multiple channels are reserved for data transmission, Request To Send (RTS) and Clear To Send (CTS) control messages are exchanged between sensor nodes, to manage the channel access and transmissions. A Reservation Channel Acoustic Media Access Protocol (RCAMAC) has been proposed for multiple channel class [Rahman, 2017].

Hybrid MAC

The hybrid is a groups of MAC protocols that combines different access technique to obtain better performance. Hybrid protocols have become an attractive research domain, many MAC protocols exist in this category, (HSR-TDMA), (H-MAC), (P-MAC), (UW-MAC), (PLAN) [Chen et al., 2014].

1.4 Routing in UWSN

The routing process plays a critical role in the WSN technology by enabling the communication between sensors, the main objective of routing is to select the more suitable path for the data to travel from source to destination [Shabbir et Hassan, 2017], taken into account the distance, the energy, and the availability of sensors. In this process many sensor nodes collaborates with each other to transmit data packets to its intended destination in a multi-hop model [Cheng et Li, 2017], it means that a transmission of packet from a source to a target will involves many sensors along the path in data relaying. The routing are challenging many water issues, due to the mobility of sensor nodes, the large scale of marine environment, and the limited battery charge lifetime. Many protocols have been implemented to ensure a long propagation delay, low bandwidth consumption, dynamic topology and energy efficiency [Awan et al., 2019].

1.4.1 UWSN Routing issues

- **Node's mobility :** as some of the wireless sensors have the ability to move within the area where they are placed, their localization might change frequently. Mobile UWSN are classified as mobile sensor node, that can moves through the ocean, besides the sensors that are anchored at the sea bed which can adjust their height, the position of a sensor can change continuously, making the routing process a great challenge [Fattah et al., 2020, Khan et al., 2018].

- **Energy consumption :** the underwater wireless devices are equipped with limited battery power, difficult to be replaced or recharged, since the operation of sensors can consume a high energy amount for their sensing process, data collection, routing process, and moving, energy might be easily exhausted. Battery depletion is a very common issue in the underwater wireless technology, given that it can affect the whole network, hence most of routing protocols are aimed to setting up an efficient method, meanwhile saving the network's overall energy [Li et al., 2016, Khan et al., 2018].

- **Channel condition :** channel conditions are presented by the communication link state, collision, ambient noises, since the UWSN suffers from connectivity loss problem according to the nodes mobility and water current factor, noises and interference from the marine environment, many routing protocol aims to select the more suitable path taken into consideration the best condition of the transmission channel [Li et al., 2016, Khan et al., 2018]..

- **Void region :** the ocean is designed as wide and large scale operating in a 3 Dimensional pattern, as the most of the sensors have the ability to move towards other regions, the density of the network might be affected, the lack of sensors presents within the network could not achieve a destination node, for the reason that the acoustic signal does not attempt a long distance over it limit, void region are areas where the signal is not reachable by sensor, in other meaning void region is a region where route to destination does not exist [Bouk et al., 2016, Hafeez et al., 2016].

1.4.2 UWSN Routing protocol classification

The routing protocols that are designed for UWSN can be classified according to different criterion's, as it is described on the Figure 1.10 :

Network Architecture based

- **Localization-based :** in this category, routing protocols depends on the sensor node's position coordination during the transmission process, to identify their location according to the source node, or destination node, or other sensors [Khan et al., 2018].

- **Localization-free :** in this class, the routing is regardless to sensors coordination, where the routing process does not require any position information of the sensors, except their depth or pressure [Khan et al., 2018].

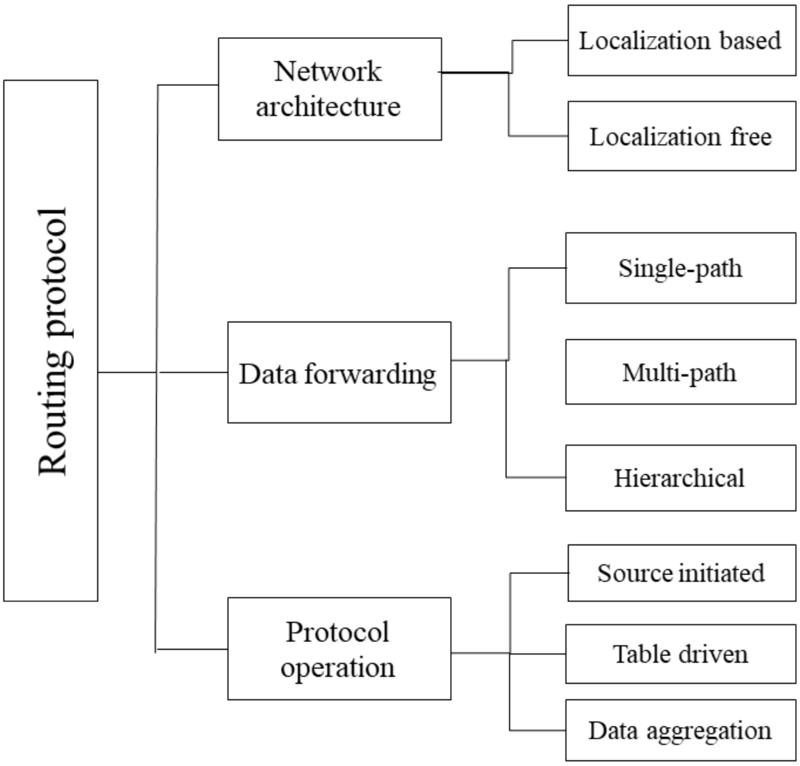

Figure 1.10 – *Classification of routing protocol*

Data Forwarding based

- **Single-path :** those protocols are aimed to establishes one path between two communicated nodes, by the estimation of the link quality, single-path protocols are aimed to provide the reliability [Macit et al., 2014, Blaise-Patrick, 2017].
- **Multi-path :** where protocols compute and use different alternative and redundant path, before sending data packets, the method allow more probabilities for that a packet can attempts the destination, and a recovery process for link failures cases [Macit et al., 2014, Blaise-Patrick, 2017].
- **Hierarchical :** where sensors are organized in cluster forms, where each cluster contains a cluster head that is responsible to gather information from the other sensor within it cluster, and communicate the data to another cluster through a gateway node, in hierarchical mechanisms, cluster can be setting up according to different level from the bottom to the surface [Misra, 1999].

Protocol Operation based

- **Source-initiated :** since the UWSN are placed in a large-scale, many routes and paths can exist between the initial sender and the target node, source-initiated protocols are aimed to find the shortest path between a source and destination node, by overcoming some link failure and breakage that might exist throughout the path, the protocols ensure the reliability of an end-to-end communication [Mao et Zhu, 2013].
- **Table driven :** in table driven routing protocols, sensors can owns many routing tables with routing information of the other sensors within the network, those tables are peri-

odically updated according to some networks shifting. The sensors use the distributed updated messages to construct and maintains their routing tables [Misra, 1999].

- **Data aggregation :** where routing protocol tend to regroup between many data packets, reduce their sizes and remove the redundant data, the method help to reduce the energy consumption by the overall network, and the bandwidth utilization [Ardakani, 2017].

Conclusion

This chapter has introduced the Underwater Wireless Sensor Network technology that is commonly explored by the scientific community in those last decade, for the numerous application and benefit that it can bring to the researcher and human beings as well, we provide an illustrated explanation about the underwater sensor functionalities and application deployment along with their physical architecture and components, besides their communication support medium that differs from the terrestrial wireless sensor, hence despite the many advantages that those technologies can bring, several challenges are encountered during their existence.

Since the underwater environment is considered as a large and harsh scheme,the researchers are rushing day by day to conceive a reliable and efficient model to enhance the wireless communication in the marine environment, and most of them are targeted the routing protocols to achieve a better performances and operation inside a given underwater wireless network, while the other are focused on the medium access layer (MAC) or even the physical layer, to attempt and improve the communication reliability between sensors, those models are classified according to some criterion and needed.

In the following chapter, we will focus on some routing protocol category, which is the localization based routing protocol, the first section contains some of the existing localization algorithm along with their challenges, the cross-layer design is introduced and some of the protocols based on it are cited and briefly explained, the following chapter includes as well a description of the well-known protocol for the UWSN 'Vector Based Forwarding', with a bright explanation of the used simulation environment, platform and tools.

Localization-based and Cross-Layer Routing Protocol 2

Contents

Introduction

Since the oceans are considered as a wide and great area covering more than half of the earth planet[Nazareth et Chandavarkar, 2020], the exploration of such an environment presents a critical challenges, as the use of the underwater wireless technologies enable to the scientific community to explore the oceans in an efficient way, numerous challenges are raising in the sensor node's positioning due to the complexity of the underwater environment [Guo et al., 2020]. Whereas the localization in the underwater networks is to determine the position of an undetermined sensor node according to a certain technique, moreover the sensor position information is required and important for some proposed routing protocols that emphases the locations of sensors as well, where the localization assumption can significantly affect the routing performances [Ahmed et al., 2017].

This chapter introduce different categories and techniques used in the localization of the acoustic sensors, where some of the proposed routing protocol that are based on localization are briefly described, in addition a new concept is introduced which is the the cross layer protocols, a category of protocols that coordinate and operate through different layer of the TCP/IP model, moreover, the underwater acoustic link quality is described along with their measurement technique and the problem of their frequent failures, the chapter include as well the well-known protocol for the underwater technologies, the Vector Based Forwarding, it description, functionality, advantages and limitations are explained, finally the simulation environment and tools used to evaluate the proposed work for this thesis are demonstrated and well explained.

2.1 Localization Algorithm

In UWSN the localization process is a critical application, due to the greatness of the ocean and marine environment, communication between sensors can be harsh to attempt during the data transmission, for that many localization schemes have been setting up to ease the communication in underwater environment. Since the underwater sensors are divided into two categories, first the static nodes, where sensors are fixed and their position are pre-configured, second, the mobile nodes where the coordination information of the sensors is unknown due to their frequent change of location, a Global Positioning System (GPS) can be used to localize the sensor nodes position in somehow [Luo et al., 2018], furthermore the GPS at 1.5 GHz band does not propagate due to the high attenuation and absorption of radio frequency in underwater [Khan et al., 2020]. Many algorithms have been proposed to identify node's positioning.

2.1.1 Classification of localization technique

UWSN consists of two nodes category which are the reference node and the ordinary node.

- **Reference node :** the reference node is a node that has already been localized and knows it position, it can be mobile anchor or a sensor node, the reference node that is attached to the surface buoy is equipped with GPS and it can obtain it coordinate information, in addiction it can obtain it depth information by using an Underwater Positioning Sensor (UPS). The reference node periodically send it current position information and the ordinary node can locate themselves using the received position information message [Su et al., 2020, Luo et al., 2020].

- **Ordinary node :** the ordinary nodes are the sensor nodes that their coordinate information are unknowns, they can locate themselves using the periodic receiving messages from the reference nodes, they can become the new reference node only if they have a high confidence value [Luo et al., 2020].

Since several methods have been elaborate and proposed for the localization process, the localization algorithms have been classified into five categories, (see Figure 2.1), according to the localization technique used by sensors.

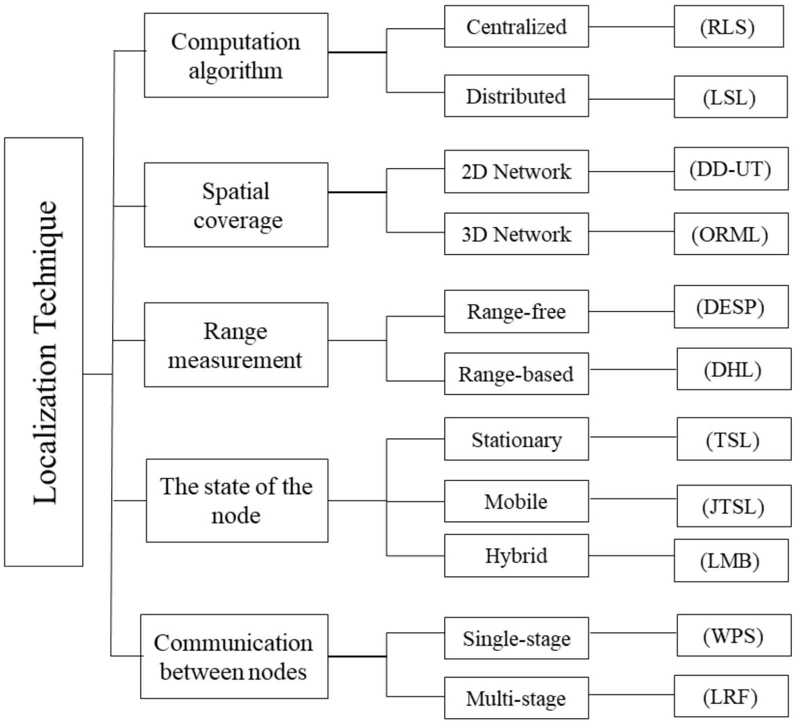

Figure 2.1 – *Classification of localization technique [Luo et al., 2018]*

- **Computation Algorithm** This category is divided into two classes depending where the location information are computed :
  1. **Centralized Technique :** where the position information of a sensor is computed at the sink node, where sensors does not know their locations in advance. A Reverse Localization Scheme (RLS) has been proposed for the centralized technique, where a 3D localization system is transferred into 2D localization, the mobile sensor nodes send the event to the surface as soon as they detect it. The localization is processed at the sink. The simulation results confirmed that the proposed scheme improves the energy efficiency and significantly reduces the localization response time with an appropriate level of accuracy in terms of water current mobility [Moradi et al., 2012].
  2. **Distributed Technique :** localization is processed in distributed way, where node's position are computed individually, and each sensor has to compute some related information as distance to it neighbors, anchor nodes, and angle information to process the localization [Luo et al., 2018]. Large Scale Localization (LSL) has been proposed by [Zhou et al., 2010], where the authors considerate only the location of ordinary node, while the surface buoy use a GPS for it localization. The ordinary nodes collect localization messages broadcasts by the anchor nodes which contains their coordination, in addition of some exchanged beacons by sensors, after collecting enough localization and beacon messages the ordinary node can estimates it location [Erol-Kantarci et al., 2011].

- **Spatial Coverage :** the spatial coverage is depending on which architecture is used for localization process, 2 Dimensional or 3 Dimensional architecture.

  1. **2D Network :** a method for 2 Dimensional network named Drift Dependent Underwater Tracking (DD-UT) has been proposed, where the anchor node which their positions are advanced known, reports their drift velocity using acoustic communication, the DD-UT has been setting up in 2D communication where the ocean current effect and sound-speed uncertainties are taken into consideration [Luo et al., 2018] the methid is based on Unscented Kalman Filter (UKF) and Extended Kalman Filter (EKF) , the two methods are a modification, of Kalman Filter (KF). UKF uses a sampling of points to approximate the probability density, this method is more efficient thant EKF in a case of a large amount of data to estimate error [Diamant et al., 2014].
  2. **3D Network :** an Orthogonal Regression Based Multi-hop localization algorithm (ORML) is proposed, due to the uncertainties of anchor node position's, the authors analyses the multi-hop distance estimation error, by applying an orthogonal regression method in order to solve the problem of node's localization in the case of error anchor position [Ren et al., 2014, Luo et al., 2018].

- **Range Measurement :** this technique is divided into two classes according to the range measurement and bearing information

  1. **Range-based :** the schemes that are range-based need the Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival (AOA) and Received Signal Strength Indicator (RSSI), to estimate the distance and convert it into coordination information [Luo et al., 2018]. A Dual-Hydrophone Localization method (DHL) is proposed in [Zhu et al., 2016] that convert the localization problem into half-plane intersection by adopting the (TDOA) measurement, the method is aimed to reduce the impact of some water disturbances,time-synchronized requirement. The DHL method tend to re-transmits only one bit binary information in case of poor link quality.
  2. **Range-free :** on the contrary of the range-based scheme, the range-free scheme are not depending on the range measurement information between, the locations of the surrounding anchor nodes are used to measure and estimate the positions [Luo et al., 2018], hence the nodes position information are not accurate compared to the range-based scheme. [Zandi et al., 2016] have proposed a Distributed Estimation of Sensor Position (DESP), that employs an AUV vehicle that will periodically transmits a messages block through four directional beams, that contains the current location of the AUV and a directional dependent marker that identify the respective beam of the message, with the estimation of the AUV's location information at two different time through two successive obtained messages beams a node coordination can be derived.

- **The State of the nodes :** in this category the localization schemes are classified depending on the state of the node

  1. **Stationary :** the network topology employs fixed node at a certain position with no ability to move, in [Beniwal et al., 2016] the authors have proposed a Time Synchronization Free Localization scheme (TSL), that consists of two steps, the first one, where the node measure it distances from three mobile beacons, through two received messages from that mobile beacon, where the second step consists to form a nonlinear equation system via the distance measurements obtained in the first step, to determine the coordination of the concerned node.

2. **Mobile :** the mobile network employs mobile node that can be free or controlled [Luo et al., 2018]. A Joint Time Synchronization and Localization Design for Mobile node (JTSL) is proposed in [Liu et al., 2015], the authors had combined between the time synchronization process and the localization to improve the accuracy of the two process jointly, where the scheme is divided into four steps, first the data collection step where node can estimate the reference time as well as the position information, to process than in the second step the synchronization, the third step consist to perform the localization, an iteration process is realized in the fourth step to update the positions.
3. **Hybrid :** the hybrid network combines and employs both mobile and stationary node, in [Lee et Kim, 2010] the authors have improved the method of [Ssu et al., 2005] which consist to estimate the location of a sensor by referring to the intersection point of two perpendicular bisectors of the chords, that is obtained by points called beacon points, since the method of the chord selection requires frequent communication between the mobile beacon and the other nodes, a Localization with a Mobile Beacon (LMB) has been proposed by [Lee et Kim, 2010] that estimates two selected node for the location of a sensor node's purpose by using geometry to determine the right location of the two elected node.

- **Communication between nodes :** where the schemes are divided depending on the communication process between an ordinary and reference nodes

  1. **Single-Stage scheme :** in this scheme category the ordinary node are localized according to the directly exchanges messages with the reference node, but once they are localized they stay passive and can not become new reference node [Tan et al., 2011]. A Wide Coverage Positioning System (WPS) for localization process has been proposed by [Tan et al., 2010], the method is aimed to improve the Underwater Pressure Sensor (UPS) that can not guarantee a unique localization with four reference node, for that the authors introduce a (UPS) that use five reference node rather than four, where the four reference node are already localized. The (WPS) is based on an infrastructure with five reference nodes but use only the beaconing from the fifth reference node.
  2. **Multi-Stage scheme :** unlike the single-stage scheme, the ordinary nodes does not communicate directly with the reference node, once they localized they became new reference node and may help to localize other ordinary node [Tan et al., 2011]. A Localization and Routing Framework (LRF) is proposed by [Erol et Oktug, 2008] where localization and routing are processed into two consecutive rounds, furthermore, a mobile beacons are used for locations servers and sink (MBS), their movement enable GPS driven coordinates. Once a node is localized it can helps for localization of other nodes by distributing self coordinate, the routing process starts after the localization round. When node has a data to send, it chooses an MBS and forward it data towards it, both position and relative motion of the MBS are used to select the best relay node.

2.1.2 Localization challenges

1. **Node's deployment :** as the underwater sensor network is deployed in a hugeness environment with 3 dimensional space, the deployment of sensors at deep water can become a critical challenge [Beniwal et Singh, 2014].

2. **Node's mobility :** the sensor network is generally composed with fixed and mobile sensors, since the mobile sensors can be controlled or free, their frequent movement can

affect the localization process, hence the estimated position of a sensor can not be accurate [Beniwal et Singh, 2014].

3. **Signal strength :** many routing protocol consider the strength of the signal in their localization process, but since the power of the signal can be affected by several sea factor as the attenuation, interference, and multi-path communication, the performance of those protocols can be seriously affected [Beniwal et Singh, 2014].

4. **Time synchronization :** due to the long underwater propagation delay and the varying sound speed the synchronization become more difficult to be achieved [Beniwal et Singh, 2014].

5. **Variation in Sound Speed :** the sound speed can be affected by the variation of some sea factors as the salinity, the temperature and the pressure of water that leads to an inaccuracy of the distance estimation by localization schemes that are depending on the sound speed parameter [Beniwal et Singh, 2014].

2.1.3 Localization-based routing protocols

Localization-based routing protocols are a sort of protocols that depends on the network information in the transmission process, where localization algorithm are used to identify the geographical information of the nodes and sink location before sending data, specifically a two or three dimensional coordinates of the sensor nodes are required for determining the routes from the bottom to the water surface as well as distances between sensors [Khalid et al., 2017].

As the node's position may change periodically due to their mobility or some ocean factor as water current, coordination information must be updated dynamically, hence more energy is consumed and wasted [Khalid et al., 2017] [Khan et al., 2018]. localization-based routing protocol are aimed to reduce the blindness of the routing discovery, however the expensive underwater GPS devices and the complexity of the localization algorithm may affect the routing performance, hence, the localization-based protocols are intended to find the most simple approach to find the location information [Li et al., 2016].

A Novel Efficient Forwarding Protocol for 3-D (NEFP) : [Qingwen et al., 2016] have proposed an approach to improve transmission efficiency with avoiding unnecessary transmission, balance the energy consumption and collisions. In (NEFP) the packets transmission from a source to an intended destination is performed as follow: At first nodes must knows their locations and carries in their packets localization information of the source, forwarding nodes and destination nodes, upon a packet is received by a node it first calculates its transmission area and checks if it is within this area, in order to avoid unnecessary transmission, after that a retention time interval is computed to balance the energy consumption and reduce the collisions in the neighborhood.
The probability of transmission is modeling by Markov Chain in order to solve the problem of inaccurate transfer caused by the frequent change of the network topology. The transmission zone method and the probability of transmission with the Markov Chain adopted by NEFP enables the node to be closer with the destination. The simulation results have shown that the NEFP outperforms in term of avoiding unnecessary forwarding, reducing the packet collision, and balancing the energy consumption. Whereas in a sparse conditions the forwarders becomes less to find which decrease the performance of the protocol [Khan et al., 2018]. The Figure 2.2 represents the network model of the proposed protocol.

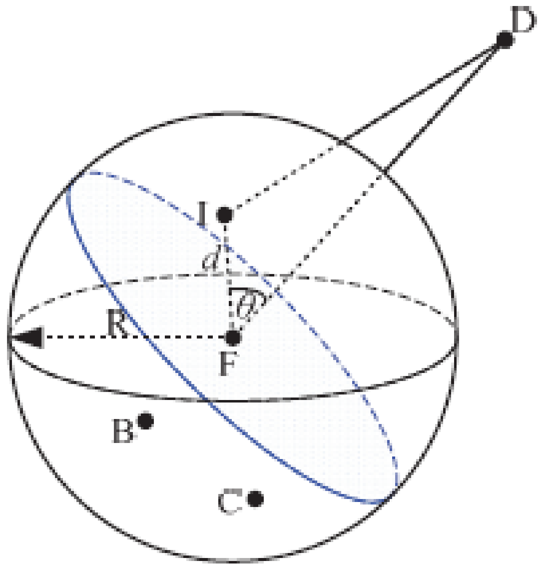

Figure 2.2 – *A Novel Efficient Forwarding Protocol for 3-D (NEFP) [Qingwen et al., 2016]*

Energy Efficient Multi-path Routing Protocol (EEMR) :

The most of the proposed routing protocol based on the flooding phenomenon, where the messages are sending multiple times without any efficient manner, are consuming and wasting a high amount of energy that affect the network performances, to overcome this strategy problem a novel routing scheme has been proposed by [Khalid et al., 2019], the approach is aimed to avoid flooding and multiple message copies and to enhance the energy consumption by nodes as well as the packet holding time.

The approach employs multiple sink that are operating at the water surface, as it is depicted on the Figure 2.3, at first, a set-up phase is processing where the nodes send request packet to their neighborhood that includes the following information : residual energy, depth information, node ID and distance from sender node, the receiver node will reply with a REPLY-HELLO packet. A table is creating at each node depending on the information including on the HELLO packet. The nodes with a lower depth than the sender node are retain in a small priority table that contains the priority value (VP) of each selected node with a defined formula, the higher VP value of a node is more its chance to be selected as forwarder is, once the node is selected its status is verified with the Ready To Send and Clear To Send mechanism to check if it is available to send or not, otherwise another node is selected.

Mobile Energy Efficient Square Routing Protocol (MEES) :

In order to balance the energy consumption and covering a maximum area of the network [Walayat et al., 2017] have proposed a new approach that is aimed to balance the load on the nodes and reduce the distance between a source and destination node, the authors had placed only two mobile sinks for collecting data sensing by multiple sensor nodes rather than a multi hopping communication, and both of them moves into a clockwise directions. First sensor nodes are randomly deployed in a square form, this one is divided into ten square regions and each regions is divided into multiple sub regions the one of the mobile sink covers the first part of the square, while the other one covers the second part, as it is shown on the Figure 2.4.

At the beginning, sensor nodes have to discover the mobile sinks by sending a hello message

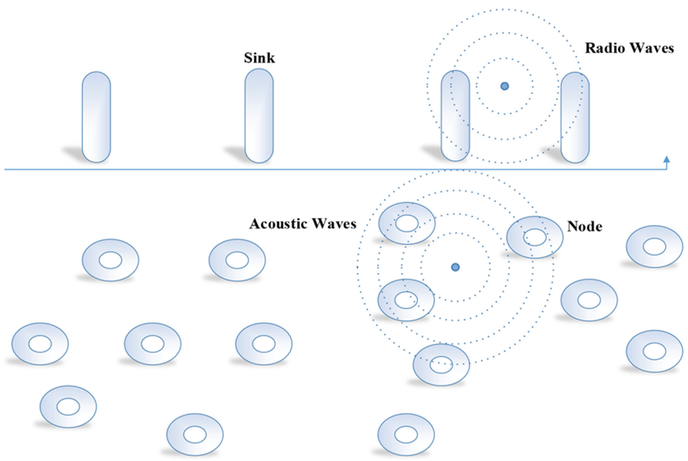

Figure 2.3 – *Energy Efficient Multi-path Routing Protocol (EEMR) [Khalid et al., 2019]*

to the mobile sink which should reply with an ACK message containing its location information. The sensor node is eligible to transmit data to the mobile sink if only the transmission range is greater than the distance between node and the sink and its residual energy is greater than the transmission energy. MEES has reached the coverage of a maximum network field and has extended the network life time as well, but suffers from packets drop and loss beside that the network performance decreases in a sparse conditions [Khan et al., 2018].

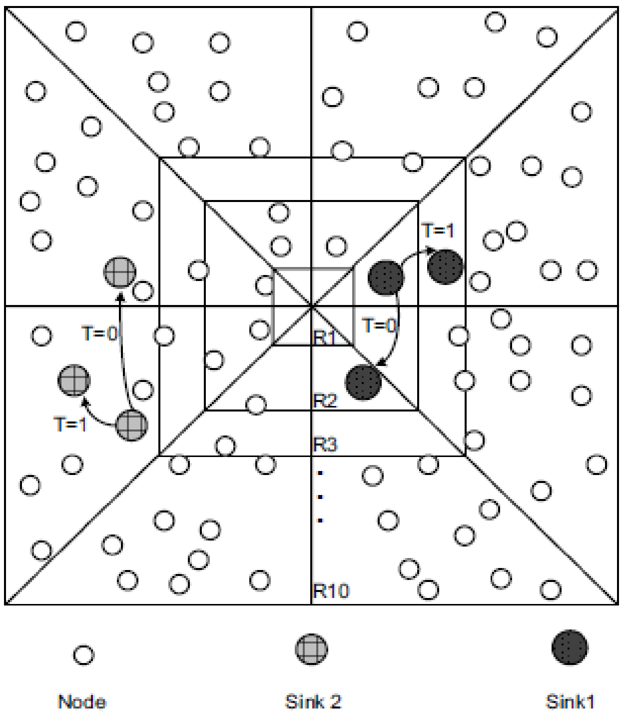

Figure 2.4 – *Mobile Energy Efficient Square Routing Protocol (MEES) [Walayat et al., 2017]*

2.2 Cross-Layer design

The communication between devices involves many complex functions that are organized and piled up into different layers, and each layer use the service provided by it lower layer, the communication between layers is ensured by a set of network rules defined by the TCP/IP model that provides the facility of the communication between the interconnected network devices. The TCP/IP model is organized in four layers as follow : the link layer, the network layer, the transport layer, and the application layer [Mao, 2010]. The cross-layer design is a method that allows the different layer communicate and share information with each other in an efficient way, (see Figure 2.5) in such a way to explore every advantage that a layer can bring.

The layered structure is not neglected by the cross-layer method, but rather, it weakens the bounds between the layers. The design has been implemented to enhance the network performance and provide a better QoS services for networks, by increasing the information sharing while reducing the communication cost [Li et al., 2016].

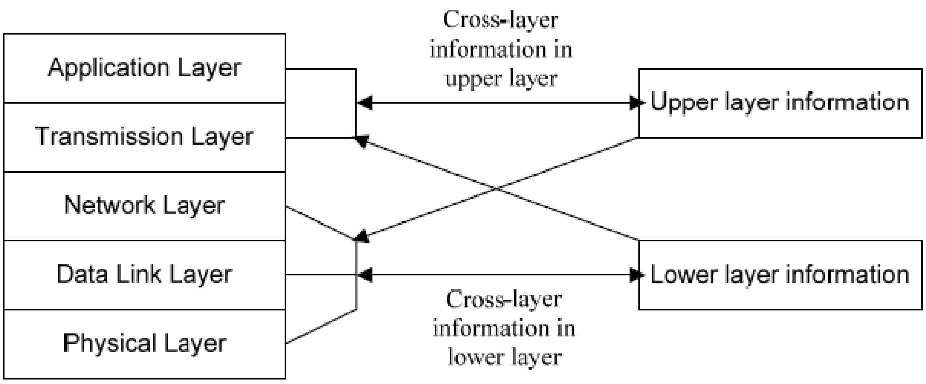

Figure 2.5 – *The cross-layer design [Li et al., 2016]*

2.2.1 Cross-Layer routing protocol

A routing protocol must be designed to optimize and provide a better performance for a network communication by taken into account various aspect designs and requirements, while the existing routing protocols can bring a good performance for an overall network performance while some of aspects may not be very effective. The necessity of developing a protocol based on a cross-layer design which merge between the protocol layer functionalities for the purpose to deliver the sensed data using the best available paths [Atto, 2016]. The cross-layer routing protocol are mainly classified into two categories depending on the network architecture, as follow :

Localization-based

The cross-layer protocol based on the localization use the underwater GPS for the position location process of the sensor nodes, those protocols are more effective than the localization-free [Li et al., 2016].

1. **Novel Cross-Layer Routing Protocol based on network coding (NCRP) :** [Wang et al., 2017] have proposed a new approach that use the network coding and the cross layer design to efficiently forward data packet in a greedy manner. NCRP combines between

the transport and the network layer, as the Transfer Control Protocol (TCP) is not suitable for the underwater environment, the method uses the network coding based hybrid ARQ protocol (NCHARQ) a transport protocol that regroup the original data packets into several encoded blocks, then the data are sent block by block.

The approach is mainly divided into two steps : initial routing construction where the initial routing path are constructed the purpose is not to find only an effective path but including auxiliary nodes that will assist the data transmission and the route maintenance, beside that the destination node is responsible for sending beacon messages to all the nodes, for the purpose that the reachable node can find the path with the destination node, the nodes close to this path are included to the auxiliary nodes list. The second step consist of route maintenance where the method delete the nodes with an inefficient transmission and without updating neighborhood information. NCRP reduces the packet collision, avoid the route breakdown, decreases the energy consumption and provide a more efficient data transmission.

2. **Cross-layer Protocol Stack Development (CLSD) :** a three-dimensional cluster-based routing protocol for underwater acoustic sensor has been proposed by [Dhongdi et al., 2017], where the network is organized as a group of many cluster deployed at different depth from the bottom to the sea surface, the approach combines between the physical layer, data link layer, and the network layer protocols.

   CLSD explore the physical layer to choose the optimal power level, while at the MAC layer the protocol adopts the sleep-wake mechanism along with a predefined time slots for the transmission and reception process to route the data packet with data aggregation, meanwhile, the network layer makes use a forward link to transfer the control information packet and a reverse link for data collection from the cluster head CH to a special node located at the water surface called BS, the routing process is done through a backbone link formed by the initial deployment of nodes and the CH selected. CLSD has provided a good data reliability, however the fact that the protocol use different routing path to route packet, leads to a high energy consumption [Khan et al., 2020].

Localization-free

The cross-layer protocol with no locations information needed are called localization-free, in which the routing process is regardless to the position information [Li et al., 2016].

- **Network Aware Adaptive Routing Protocol(NADIR) :** a self-distributed and adaptive cross-layer protocol has been proposed by [Petroccia et al., 2018], the approach can work with both static and mobile devices and use the link quality and the energy consumption obtained from the physical layer as a key parameters to determine how the data packets can be routed. The protocol is mainly composed of two phases, where the first one consist to obtain some nodes information such as : number of hops from the neighbor to the concerned destination, the supported communication schemes, the presence of mobile nodes, and the link quality obtained from the physical layer in a cross-layer manner and provided in the form of Packet Error Rate (PER), the required energy to transmit the information to the neighbors.

  While in the second phase the packet is routed and meanwhile the control messages are exchanged between nodes if any changes occurs during transmission process. (NADIR) has provided a good performance in term of number of delivered packet, and energy consumption with an unreliable acoustic channel, whereas it has provided a less efficiency in term of the average time taken for data packets to be delivered since there is no retransmission of packet loss

- **An AUV-Aided Cross-Layer Mobile Data gathering (CLMD) :** in this approach, proposed by [Alfouzan et al., 2020], the nodes are organized in cluster, which every cluster has it cluster head (CH), the CH nodes are selected based on their priority, closeness to the sink, and their residual energy, meanwhile, an Autonomous Underwater Vehicle (AUV) is used to periodically collect data from the CH node. At the end of each operational phase the CH node are replaced with other candidate node in order to maximize the network lifetime. (CLMD) is a cross-layer mechanism that integrate the routing and the MAC layer, the method is operating according to four steps : the first step is the neighbor discovery phase where control packet are exchanged to establish the neighboring table, while in the second step a distributed clustering is processed by selecting the most desirable cluster head (CH) with a high priority value that depends on the node degrees (one-hop neighboring degrees), the distance to the sink, and the node energy.

  AUV discovery phase, while the AUV travels throughout the network it broadcast a small beacon messages, and the nearest CH will reply to the AUV with small beacon messages to be added in the AUV's list. A normal operational phase that is composed of two steps, the first step consist to gather data from the CH nodes by the AUV that will upload the gathered data to the sink, while the second step is an intra-cluster communication, in which the sensors are exchanging frames within certain time slots. The protocol has provided a good performance in term of energy optimization, and has extended the network life time.

2.3 Acoustic link quality in UWSN

With the continuously advancements in wireless technologies over the past few decades, the application of underwater wireless sensors is recommended to collect sensed phenomenon from the marine environment as the oceans [Nazareth et Chandavarkar, 2020]. However The Underwater acoustic network environment are frequently confronted to several constraints, as the limited bandwidth, lower speed and high propagation delay [Khasawneh et al., 2020], which can significantly affect the network performances. The link quality is one of the most important factors, as the underwater wireless sensors presents some limits as the limited bandwidth and battery power, intermittent topology due to the mobility or water current, the link quality of the wireless communication may deteriorate which has an impact on the delivery data packet, the delay time and the energy consumption. The link quality is varied and dynamic depending on the distance between sensors, their depth information, and other underwater characteristics [Nazareth et Chandavarkar, 2020].

2.3.1 Acoustic link quality measurement

The link quality measurement is defined by the signal to noise ratio (SNR), where the link quality is measured depending on the signal and noise ratio, and depends on multiple parameters as the source level, transmission loss and noises. Moreover a high value of SNR indicates a low chance of an error in a transmitted packet [Nazareth et Chandavarkar, 2020, Domingo, 2008]. SNR is defined with the following formula :

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

where SL represents the source level, TL is the transmission loss which is depending on the temperature and salinity of the water, distances and depth of the sensor node, N is the noise level, and DI is the directivity index.

Channel noise

UWSN technology are facing multiple noise sources, those noises can be provide by human beings due to their machinery activities, fishing, and military activity, as it can be induced by other reasons as turbulence, shipping, waves and thermal noise [Awan et al., 2019]. However each noise sources have there Power Spectral Density (PSD) and are represented as N_{tr}, N_{sh}, N_{wv} and N_{th} respectively [Qadar et al., 2018]. Hence the (PSD) of total noise N in dB is given with following formula :

$$N = N_{tr} + N_{sh} + N_{wv} + N_{th} \tag{2.2}$$

Where N_{tr}, N_{sh}, N_{wv} and N_{th} are defined as :

$$10logN_{tr}(f) = 17 - 30log(f), \tag{2.3}$$

$$10logN_{sh}(f) = 40 + 20(s - 0.5) + 26log(f) - 60log(f) + 0.03, \tag{2.4}$$

$$10logN_{wv}(f) = 50 + 7.5w(\frac{1}{2}) + 20log(f) - 40log(f + 0.4), \tag{2.5}$$

$$10logN_{th}(f) = -15 + 20log(f). \tag{2.6}$$

where f represents the frequency in KHz, w represents the speed of the wind (m/s) and s defines the movement factor of shipping [Qadar et al., 2018]. All the noise sources affects the signal quality as they are added to the desired signal power [Stojanovic, 2007].

The acoustic signal attenuation

The UWSN technology are using the acoustic wave communication systems as a physical medium for the transmission of information, for the reason that the acoustic waves presents a better performances compared to the other types of waves [Benabdallah et Hammad, 2013], since the Radio Frequency and the Optical signal are not suitable for marine environment [Luo et al., 2018], Aqua-Sim has been introduced to support such a communication type.

As any other communication support, the acoustic signal tend to be reduced during it transmission, due to several aquatic interference and noises, the reduction of the signal is called attenuation, hence the attenuation of the acoustic signal attenuation is calculated based on the spreading loss of the signal, along with the signal absorption loss, at a certain given frequency f [Khasawneh et al., 2018] the attenuation formula is given by [Stojanovic, 2007] The absorption loss $\alpha(f)$ is expressed by the following formula :

$$10log(A(l, f)) = k \times 10logl + l \times 10log(\alpha(f)) \tag{2.7}$$

Where l defines the distance between two sensors, k is the spreading coefficient, and $10log(\alpha(f))$ is defined by :

$$10log(\alpha(f)) = \begin{cases} \frac{0.11f^2}{1+f^2} + \frac{44f^2}{(4100+f)} + 2.75 \times 104f^2 + 0.003, f \geq 0.4 \\ 0.002 + 0.11(\frac{f}{1+f}) + 0.011f, where f < 0.4 \end{cases} \tag{2.8}$$

where $\alpha(f)$ is measured in Decibel (dB) and the frequency f in Kilo Hertz (kHz). The absorption loss value α is derived as $\alpha = 10^{\alpha(f)}/10$.

The received acoustic signal strength of a given node is calculated as :

$$RSS_A = \frac{Tr_{power}}{A(d(A,S),f)} \quad (2.9)$$

Where Tr_{power} is the initial transmitted signal power.

The link quality of the acoustic communication has to be evaluated and considering by the routing protocols in the next sensor node selection by taking into consideration the signal to noise ratio (SNR), and the received signal attenuation as well, some of the proposed works

2.3.2 Acoustic link failures

Failures and interruption of wireless link are a common problem within the wireless network due to numerous reasons, since the underwater sensors are deployed in a large environment, link and nodes failures are frequent, for several reasons as the sensors are equipped with a limited battery, nodes are more prone to fail, in other hand the frequent change of nodes position due to it mobility or water current affect the received signal strength which may result in a a poor link quality, in addition the presence of interference, and noises affect severally the received signal. Inefficient link quality may generates link interruption between sensors. The major problems that induces to failures are explained as follow :

- **Energy constraints :** as the underwater sensors are equipped with a limited battery that is not easy to recharge or replace, a sensor can easily consume it stored energy due to the frequent required computation algorithm, when a sensor has no more remain energy, it causes its death [Shaikh et Sayed, 2015], the sensor become no longer operating, and it is called node failure, which result in the lost of the connectivity [Goyal et al., 2018].
- **Interference and noises :** when a signal is issued from a device with a certain transmitting power, it can be confronted with many underwater environment interference as other wireless sensors, enormous rock and boat, and marine animal, that makes the signal attenuates more and more and reduce it received strength. Moreover, noises occurred due to different sources which affect the transmitted signal as : wind, shipping, thermal, and the turbulence [Awan et al., 2019].
- **Node's mobility :** since the mobile sensor nodes are frequently moving towards random direction, a mobile node can quit the transmission range of it sender during the transmission process, which result in a weak received signal, and communication failure [Li et al., 2016].

Several effects can be induced by the nodes or link failures of the acoustic communication :

1. **Localization :** due to the marine current in a major time the underwater devices can be drifted from their actual position, some of them have the ability to move towards different region which may severally affects the network topology, precisely the location of sensors that caused the inaccuracy of their localization [Beniwal et Singh, 2014], since that some of the existing routing protocol are localization based, which requires the position coordination information to establish routing path and transmit data packet [Khalid et al., 2017], hence the movement of sensors affects the localization of the underwater sensors.
2. **Void regions :** due to the frequent movement of sensors, the wireless devices can move towards region in which the acoustic signal is not well received for the reason that the acoustic waves is considered as a low propagated signal and can not attempt a long distance over it limit, this region are called void regions, moreover the presence of few sensors within a network could not make a data achieve it intended destination, hence

the void regions or holes are areas where route to destination does not exist [Bouk et al., 2016, Hafeez et al., 2016].

3. **Intermittent topology :** link failures have another disadvantage and impact on the route creation and their maintains, which causes the topology changes dynamically [Gao et al., 2016]. The continuous change of network topology may results in energy consumption, where sensors are required to recreate new path as well, moreover the rate of the successful delivered data is several impacted, due to the many loss of packet during network topology change [Gao et al., 2016, Ahmed et al., 2017]. Routing protocol that provide immediately route recovery should be designed for the underwater technology.

4. **Connectivity loss :** during a transmission and exchanging messages between sensors, a wireless device could easily drift away from it sender's range, while the sender is sending a data packet, hence the wireless link quality become unreliable, the signal is weak for the packet to be received, the link is considered as fail or interrupt. The wireless connection and the quality of the link has to be measured and evaluated before that a sender issues a data packet [Li et al., 2016].

2.3.3 Acoustic link and node failures prediction

Due to the continuous link and node failures issues, it is useful to predict future link interruption in order to recover data packet which may be lost and enhance the performance of routing protocols, several methods and mechanism have been proposed to evaluate and estimate the possibility of the node failure that can affect the network topology, detect the mobility and predict link interruption[Lu et al., 2013, Zonouz et al., 2014, Bao et al., 2018, Agarwal et Rakesh, 2017, Raj Priyadarshini et Sivakumar, 2020]. In this thesis, our main focuses are to predict failures due to the mentioned reasons and prevent from such an event in earlier time, for that, we have exploited the advantages of the Polynomial Interpolation that can bring for the estimations in different context.

Polynomial Interpolation

In mathematics, considering a data point x, the estimation of the value or function *f(x)* according to known values of the function is called interpolation as it is depicted in the Figure 2.6. Given (x_0..x_n) with their respective functions (f(x_0)..f(x_n)), if x_0 < .. < x_n and y_0 = f(x_0),..., y_n = f(x_n) are already known, and if x_0 < x < x_n, the estimated value of f(x) is an interpolation, else if x < x_0 or x > x_n, then the estimated value of f(x) is an extrapolation [Britannica, 2016]. There are many such functions for the interpolation as Newton Interpolation, Lagrange Interpolation, Hermite Interpolation, Spline ..ect, hence in this thesis, the Newton and Lagrange Interpolation are used and exploited in order to evaluate the link efficiency, where the Lagrange and Newton polynomials are the most commonly used methods for interpolation [Shyu et Ytreberg, 2011] where the x values are considering as the received time of the acoustic signal, and the *f(x)* values are their respective signal strength, to measure the predicted signal at t time.

2.4 Vector-Based Forwarding Routing Protocol VBF

VBF is a routing protocol for underwater wireless sensor network (UWSN), proposed and implemented by [Xie et al., 2006] based on the localization and the position information of sensors to forward the data packet, while the nodes are deployed at different depth, the source node is located at the sea bed, and the destination (SINK) is deployed at the water surface, VBF protocol employs a technique based on a vector, which means that there is virtual routing

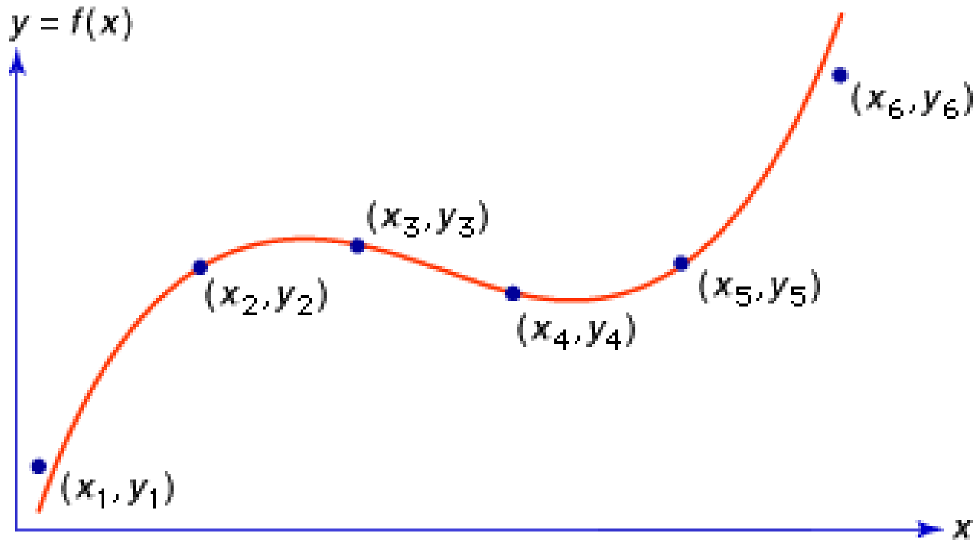

Figure 2.6 – *Polynomial Interpolation.*

vector formed by the source and destination node, the nodes located near the vector at a certain predefined value are eligible to forward the packet coming from the source to the destination node in a hop by hop communication, those nodes are forming a virtual routing pipeline as a cylinder shape around the vector, nodes which does not belongs to this pipeline are simply ignoring the forwarding process.

Packet

OP	FP	TP	RADIUS	RANGE

Figure 2.7 – *Vector Based Forwarding routing protocol Packet [Xie et al., 2006].*

During the transmission, each node carries in the position field of its packet the coordination of the source node OP, the destination node (target) TP and the forwarder node FP, beside that each packet contains a RANGE field used by the target to flood the received packet through an area controlled by this value. Another field is carrying by the packet which is RADIUS field, a predefined threshold value used by sensor to determine if they are closed to the vector. Once a packet is received by a node it will computes it distance with the vector if it is less than the mentioned RADIUS value, the node will then put it own position coordination in the packet and forwards it, otherwise the node will discards the packet.

As it is shown on the Figure 2.8 the routing vector is formed by $\overrightarrow{S_1S_0}$, the RADIUS of the generated routing pipeline is denoted by W, all the nodes located near the vector, inside the pipeline are forwarding the packet.

2.4.1 Packet types of VBF

In VBF, events prevention and area location information are made through multiple query packets :

1. **INTEREST :** when the sink node is interested to know the location or events of a specific

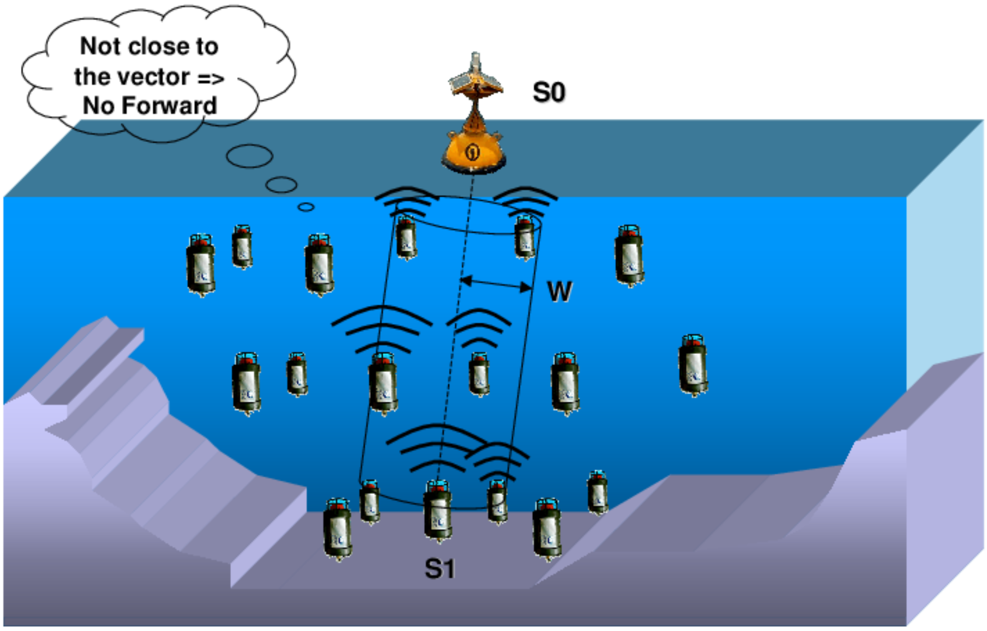

Figure 2.8 – *Overview of Vector-Based Forwarding Routing Protocol [Xie et al., 2006].*

area, it will broadcast an INTEREST query packet, the node that has the data which the sink is interested on will reply.

2. **DATA READY :** this packet type is sending from the source node when it senses some events and want to inform the sink.

3. **SOURCE DENY :** when a source node is moving out the area which the sink is interested on it, the sink will then send a SOURCE DENY query packet to inform the source to stop sending the data.

2.4.2 Query process in VBF

There is two types of queries sending messages in VBF, query forwarding and source initiated query, the first query is processing by the sink node, while the second query is initiated by the source node.

Query Forwarding

In the query forwarding, there is two different types, the location-dependent query, where the position information are needed to query packet, and the location-independent query where the position information are not necessary.

1. **Location-dependent query :** when the sink node is interested to know the location of a specific area it will broadcast an INTEREST query packet, this packet will contains the position coordination of the sink and the target, when a node receive the packet it will determine if it is close enough to the routing vector using the threshold value denoted by the RADIUS field, if it is so, the node will update the FP field, setting it own coordinate and forwards it, till the packet is received by the source node which is the target.

2. **Location-independent query :** when the sink wants to know some underwater information, as temperature, pressure or other else regardless of its location, it will send an

INTEREST query packet, in this case when a node receives such a packet it will check up if it has the information sought by the sink, if it is so, it will first computes it belonging to the routing pipeline, and then put it own location information, generates the concerned data packet and sending it to the sink node, however if the node does not have the concerned data it will update the FP field of the INTEREST packet and forwards it.

Source initiated Query

When the source node senses some particular events and wants to inform the sink node, for that it will initiates a DATA READY packet query, the nodes throughout the pipeline will defines first if they belongs to the pipeline to forward such a data packet, once the sink node receives this packet it will decides if it is interested by this events issued by the source, if it is so, it will initiate an INTEREST packet to the area where the source is located.

2.4.3 Sink-assisted approach

A source node can keep moving and get far from it initial location, the problem is when the sink node is initiated the INTEREST packet to prevent the source that it is interested in some events, the location of the source will not be accurate, that can affect the routing of this packet, for that a sink-assisted approach is proposed by [Xie et al., 2006] to solve this problem, when the sink received multiple packet by the source node it will determine if the source is moving out the scope as follow : Assuming that the position of the sink is $P_c = (x_c, y_c, z_c)$ based on the source coordination that is $P_{source} = (x_{source}, y_{source}, z_{source})$ and the real position of the sink is $P = (x, y, z)$. The sink computes it position according to the source coordination, as $(\delta_x, \delta_y, \delta_z) = (x_c - x_{source}, y_c - y_{source}, z_c - z_{source})$, then the real position of the source is computed as : $P'_{source} = (\delta_x + x, \delta_y + y, \delta_z + z)$
Now the sink node compares between P'_{source} and P_{source} and can determine if the source is moving out the range, if it is so, the sink will send a SOURCE DENY query packet to prevent the source to stop sending data.

2.4.4 The Self-Adaptation Algorithm

The VBF protocol allows only the sensor nodes close to the routing vector located within the virtual pipeline to transmit and forward data packet, hence when the network is densely deployed, the virtual pipeline can contains a lot of sensor nodes involved in the forwarding process, that can generates a high energy consumption, for that [Xie et al., 2006] have proposed a self-adaptation algorithm based on the node density that will adjust the forwarding policy, in such a manner that each node will first estimates the density of it neighborhood before holding the packet a certain time according to it desirableness factor value, this value determines the suitableness of the node to forward the packet

Desirableness Factor

With the Figure 2.9 given below, assuming that the routing vector is given by $\overrightarrow{S_1 S_0}$, where the source is S_1 and the target is S_0, the node A will first computes it desirableness factor to measure it convenience to forward the packet, which it is defined and calculated by the following formula

$$\alpha = \frac{P}{W} + \frac{R - d * cos\Theta}{R} \tag{2.10}$$

Where P is the projection of the node A to the routing vector $\overrightarrow{S_1 S_0}$, W is the radius of the virtual pipeline, R is the transmission range, d is the distance between the node A and the routing vector $\overrightarrow{S_1S_0}$, θ is the angle between the vector $\overrightarrow{FS_0}$ and $\overrightarrow{FS_1}$. By measuring the desirableness factor value of the node, it can determine if it is in the best position to forward or not, if the desirableness factor is large, it means that even the projection of this node to routing vector is large, the node is not in an optimal position and it is not desirable for it to forward. After that a node has received a data packet it has to determine if it is close to the routing vector, if it is so, it has to estimate it suitableness to forward, then the node hold and delay the packet a certain time interval according to it desirableness factor value, this time interval is defined as :

$$T_{adaptation} = \sqrt{\alpha} * T_{delay} + \frac{R - d}{v_0} \quad (2.11)$$

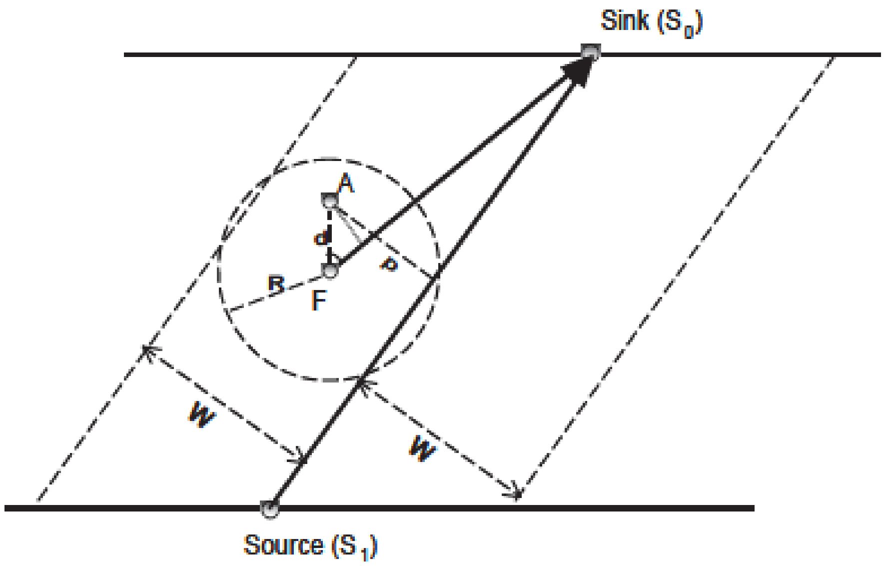

Figure 2.9 – *VBF Desirableness Factor [Xie et al., 2006]*

Where α is the desirableness factor, T_{delay} is predefined maximum delay, d is the distance between the node A and the forwarder F, v_0 is the propagation speed of the acoustic signal in the water (1500 m/s). When the desirableness factor value is small, the time to wait is less and vice versa.
The first term of the formula is the waiting time according to the desirableness factor of the node A, while the second term is the additional time to wait for that all the nodes in the transmission range of the forwarder F to receive the acoustic signal from the forwarder.

1. **Duplication packet :** while the node is delayed it packet before it can forward it, multiple duplicated packet can be received from other node, for that the receiver has to compute it desirableness factor according to these nodes and the original forwarder of the packet, then the minimum value is compared with a predefined initial value α_c as follow :
min $(\alpha_0, \alpha_1, ...\alpha_n) < \alpha_c/2^n$, where α_c is defined as $0 \leq \alpha_c \leq 3$. If the condition is verified then this node can continue forwarding the packet, otherwise it has to discards it.

2. **The revaluation of the desirableness factor :** the self-adaptation algorithm allow the most desirable node to forward the packet, and allow the less desirable node to re-valuate it suitableness among it neighbors. During the re-valuation of the importance of node, if there exist many more desirable nodes than the less desirable, the algorithm reduce the probability of the node to forward the packet, in order to balance the energy consumed. In other hand if the less desirable node is delayed it packet forwarding after re-valuating

it importance among it neighbors, and has received more than two duplicated packet, this node will not forward the packet no matter what the initial value α_c is, there exist more desirable qualified node.

By referring to the Figure 2.10, the routing vector is formed by $\overrightarrow{S_1 S_0}$, the actual forwarder is the node F, and the nodes, A, D are receiving the packet forwarded by the node F, the self-adaptation algorithm gives the priority to the most desirable node, in this case the node A will first send the packet, for the reason that it desirableness is the smaller one, it projection value is 0, so it is considered as the optimal node, thereafter the node B is within the transmission range of the node A and it is considered as a less desirable node beside the node A, so it has to re-valuate it importance and decides if it has to forward the packet or not, meanwhile the node D is not within the transmission range of the node A so it can forward the packet.

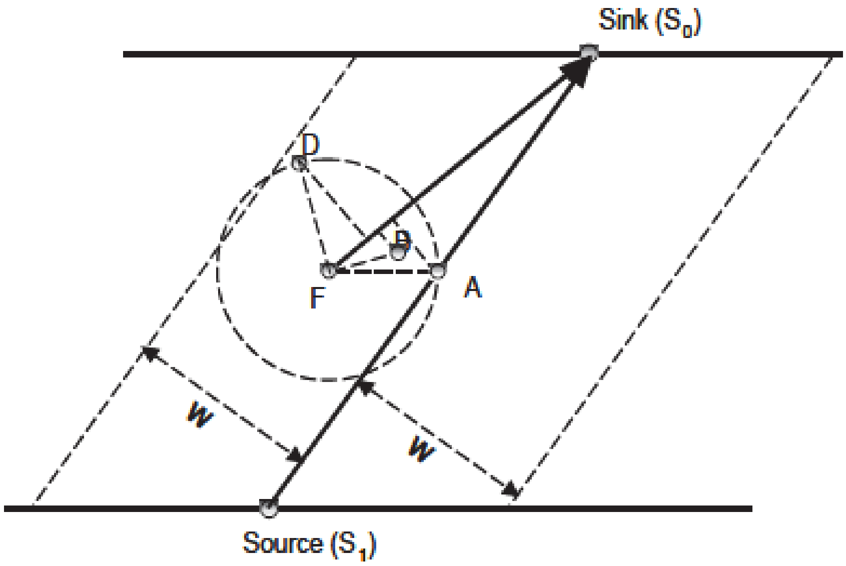

Figure 2.10 – *VBF Self-adaptation Algorithm [Xie et al., 2006]*

2.4.5 The implementation of MAC protocol

Since the UWSN are suffering from additional limits, as limited bandwidth, high propagation delay, energy consumption, and dynamic topology, beside the use of the acoustic communication medium, The existing MAC protocol for the Ad Hoc networks such as the terrestrial wireless network are not suitable for the Underwater wireless network technology, hence several MAC protocol such as (Broadcast MAC Aloha, Tu-MAC and R-MAC) have been designed and derived from a common class, where the most public interfaces used by the MAC protocols are defined [Xie et al., 2009].

- **Broadcast MAC :** this MAC protocol is based on the CSMA that has to sense the channel before any transmission. In this MAC protocol before that a node sends a packet it has first to check if the channel is busy or free, for that it sense the channel, if the channel is free the node broadcast it packets, otherwise if the channel is busy the node makes use a back-off algorithm before sending packet, the maximum number of back-offs has been limited at 4, since the algorithm has no mechanism to detect collision, no exchange of control messages (RTS/CTS), and no acknowledgment packet, the MAC protocol limits the sending rate of messages at 2 per second in order to avoid packet interference [Xie et al., 2006], the Broadcast MAC takes the advantage of the acoustic communication broadcast and it is appropriate for the geo routing protocol such as VBF [Xie et al., 2009].

2.4.6 The robustness of VBF

The evaluation and the experimentation of VBF has proven the efficiency and the scalability of the protocol since it is a localization-based that addresses the node's mobility in an efficient way where the position information of a node is computed locally and does not requires a global synchronization. The mobility of the node is used as a parameter to help for the selection of other forwarder nodes during the forwarding process [Khan et al., 2018]

- VBF does not requires a stable forward path, since many other forwarder can be involves in the forwarding process along the pipeline.
- The routing does not need any state information for all the nodes.
- Only nodes close to the routing vector are eligible to forward data, the nodes outside the pipeline stay in an idle state till they moves close to the vector, thus helps to save the network energy.
- Since the self-adaptation algorithm select the more desirable node to forward, more energy is saved.
- VBF requires at least on available path inside the virtual pipeline, for that the packet can successfully transmitted.
- The computation appropriate for routing on each node are on demand only.

2.4.7 VBF Limitations

Even if VBF is robust against node failure, and it have the advantage to reduce the energy consumption by selecting the most desirable nodes, except that the protocol presents some weaknesses that can affect the reliability of the routing :

- VBF does not have the functionality to re-transmit the packet, if the sensor node does not receives it due to weak received signal strength, or collision problem [Abbas et al., 2019].
- Due to the limited stored battery power of the devices, the sensor nodes that are frequently qualified to forward data packet can be easily exhausted and failed [Nicolaou et al., 2007].
- The number of forwarding node are limited due to the routing pipeline radius, and more efficient path can exists outside the pipeline that leads to the sink node, hence the routing performance can be severally affected [Nicolaou et al., 2007].
- VBF suffers from void holes as the sensor nodes are deployed in a large environment, the void holes are the sensor nodes with no path leading to the next destination or forwarder node, that causes an important loss of data packet [Yu et al., 2015].
- When the sensor nodes forward their data packets, they does not takes into account the efficiency and quality of link with the next hop nodes, that generates at some point unnecessary transmission [Ali et al., 2014].

2.5 Network Simulator 2 (NS-2)

NS-2 is an event-driven network simulation tool and a development platform that is the most widely used by the research community since it brings an efficient methods to configure a network. NS-2 is aimed to study the dynamic nature of network communication whether it is a wired or wireless communication, and provide multiple network functions and protocol as the routing algorithms, TCP or UDP [Issariyakul et Hossain, 2009, Xie et al., 2009].

2.5.1 The basic architecture of NS-2

NS-2 consist of two languages, mainly the C++ language and the Object-oriented Tool Command Language (OTcl). The C++ defines the internal mechanism of the simulation (Protocols and algorithms), while the OTcl assembles and configures the object and schedules events to set up the simulation. The variables in OTcl domain are referred to handles that acts as an interface which interacts between users and other OTcl objects. C++ and OTcl are related with a Tool Command Language (TCLcl) file that contains a set of commands intended for the simulation scenario [Issariyakul et Hossain, 2009].

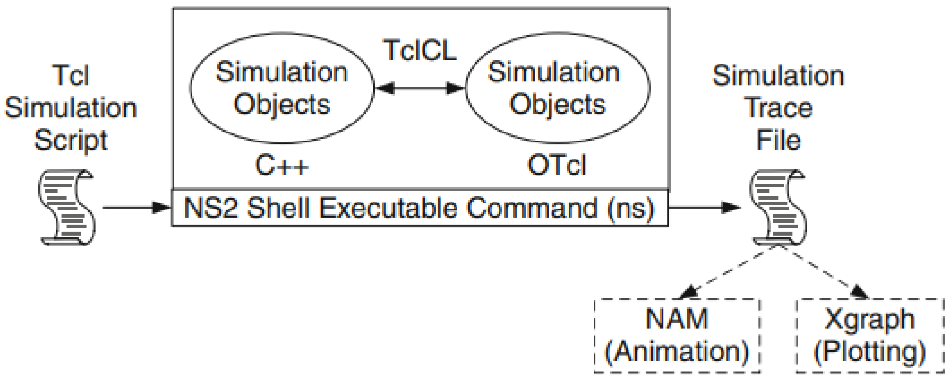

Figure 2.11 – *The basic architecture of NS-2 [Issariyakul et Hossain, 2009]*

After that the NS-2 shell executes the simulation objects according to the input script file TCLcl (see Figure 2.11), the output will be resulting as a trace file that consist of all simulation traffic including routing and MAC information, nodes positioning, simulation time, sending and receiving state, loss or a receive packet. To interprets the simulation results graphically a Network Animator tool (NAM) is used. In order to evaluate and process the trace file, a Java language file or AWK file is used to extract only the necessary information for the performance evaluation. Once the information are retrieved there is several tool that allows a better and efficient interpretation of the result mainly as XGraph, Microsoft Excel or GNUplot [AOUIZ, 2020] used to plot the retrieved information using curves for a better analysis [Issariyakul et Hossain, 2009].

2.5.2 Aqua-Simulator

The NS-2 is a simulator tool that supports only the terrestrial wired and wireless network, hence it is not suitable for the underwater wireless network simulation, since the platform does not support the acoustic signal which is commonly used for underwater environment. The acoustic signal is very different from the radio signal and has a slow propagation speed about 1500 m/s, besides that the underwater sensor network are a three-dimensional space, while the basic NS-2 support a deployment of a two-dimensional [Xie et al., 2009] have proposed a new simulator called Aqua-Sim that support the underwater environment. The aqua simulator has been implemented using the NS-2 as development platform.

Aqua-Sim Implementation

As the existed simulation package in NS-2 can not operates with the underwater network environment, as the acoustic signal provide a long propagation delay and a high attenuation, moreover the three-dimensional space is not supported by the CMU wireless package of NS-2, while the protocols of different layers are not suitable to support the underwater sensor network. To overcome this problems cited above, [Xie et al., 2009] have created a new simulation package named Aqua-Sim regardless to the existing package instead of patching on the existing CMU wireless package.

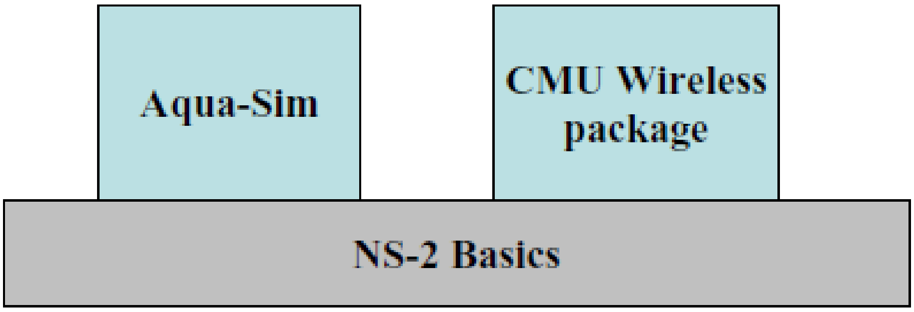

Figure 2.12 – *Aqua-Sim and CMU wireless package [Xie et al., 2009].*

The Figure 2.12 shows that the Aqua-Sim is independent from the CMU wireless package any change in the package will not affect the other package, since they operates separately.

Aqua-Sim Design

The Figure 2.13 represents the diagram of the Aqua-Sim where different functionalities of the simulator including some objects and classes that are designed according to the network simulator operating.

1. **UnderwaterNode :** is an object that consist of many useful information regarding the the underwater sensor node including mainly it position, and mobility speed. The UnderwaterNode object is available to access by all the objects of Aqua-Sim.

2. **UnderwaterChannel :** this object represents the underwater acoustic channel, where all the packets before being sent are queued at this object, moreover the "UnderwaterChannel" offers a public interface to the upper layers such as the routing layer.

3. **UnderwaterPhy :** the underwater node physical layer is represented by the "UnderwaterPhy" that offers interfaces to the upper layer that can power on and off the transmitter and adjust the transmitted power level, while updating the remaining power level of a node, moreover this object provides an energy consumption computation.

4. **UnderwaterMAC :** this class provides the same interface to the MAC layer entities such as MAC protocols (TMAC, RMAC, Broadcast MAC, Aloha MAC). It is not necessary for an object to know the detailed of the MAC layer implementation if this object want to

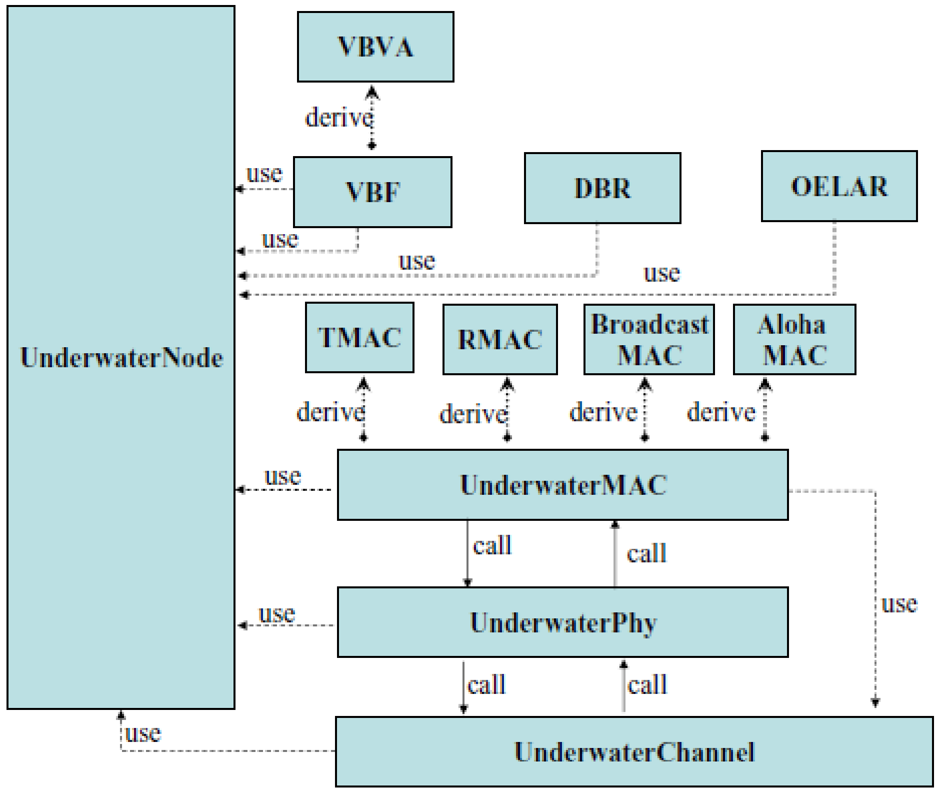

Figure 2.13 – *Aqua-Sim Diagram [Xie et al., 2009].*

send a packet to the MAC layer, the object makes uses the common "Recv" interface, that is defined in "UnderwaterMac".

5. **Underwater Network Layer :** the routing protocols for underwater network such as (VBF, DBR, VBVA, OELAR) follows the basic structure of the existing routing protocols in NS-2, hence to support the underwater communication, the protocols parameters are structured through a TCL script to make sure that the protocols support the features of the underwater environment, the Aqua-Sim tool offers interfaces to all the network layer, for the reasons that the routing protocols based on the localization can obtains the position information from the "UnderwaterNode".

Conclusion

This chapter have been focused on the routing protocols based on the localization scheme, we have presented and illustrated all the localization technique used in the major Geo-routing protocols that are based on the nodes position, beside the frequent challenges recently encountered by the localization schemes. We have introduced then, the cross-layer concept which is a design that interact between different layers which provides a new mechanism that achieves a good network performance, thereafter, some of cross-layer routing protocols that are free and based on the localization scheme are cited and explained.

The following section initiate the acoustic link quality, along with the main factors that generates failures and interruption within an underwater sensor network, and their impact over the network performances, then a detail explanation of all the features and functionalities related to the well-known routing protocol Vector-Based Forward (VBF) designed for the underwater sensor network, the protocol has proven it robustness mainly by avoiding collision, and saving the energy consumption, hence VBF represents some drawbacks that can severally and significantly affect the network performance, The sections contains the presentation of the simulation environment used in our studies, which is the widely used network simulator NS-2 that includes a new package named Aqua-Sim that support the underwater communication environment.

In the following chapter, the first contribution is introduced, that is aimed to prevent from inefficient wireless communication due to the sensors mobility and their frequent movement, the chapter include as well some of the proposed studies related to the major discussed problem, and presents a depicted explanation of the proposed mechanism.

3 CONTRIBUTION I: A Cross-Layer Predictive and Preemptive Routing Protocol for UWSN using the Lagrange Interpolation

Contents

Introduction

The underwater wireless sensor network technologies are confronted and facing several challenges due to the unpredictable conditions of water environment that may creates serious constraints in their design and deployment [Felemban et al., 2015], such as the cost of their deployment, the limited battery of the devices, the low propagation delay, the attenuation problem, and sensors localization [Awan et al., 2019] where the conception of efficient and optimal protocols that operates at different layers are required to maintain a better network functioning.

Whereas the UWSN technology frequently confronts failures and interruptions which are the common issues encountered inside a network that contains mobile devices, when a sensor is establishing a communication link with another sensor and try to join it, in some moments the node try to move in another direction that will makes the communication link stand inefficient that leads to a link failure or intermittent acoustic connectivity [Kamal et al., 2014], the performance of the network can be severally affected in those cases, particularly if the failure link is the optimal link to transmit data packet.
Several reasons can generates a link deficiency, the main cause discussed in our contribution is described as follow :

1. **The Movement of Underwater Sensor Nodes :** the underwater network is mainly composed of static and mobile devices, the static sensors can be fixed or anchored at a certain position, while the mobile devices have the ability to move towards random and different regions, and it can be controlled or free, the frequent movement of the mobile sensors can have a harsh impact on the overall network performances, which means that when a sensor is continuously moving, the network topology became unsteady due to the inaccuracy of the sensor position. Precisely, a mobile sensor can easily leave the range of it sender during a data transmission, which will make the received signal attenuates promptly, then the sensor became unreachable for it sender, in this case the routing is easily broken, and a mechanism to recover and rebuild the paths is necessary, hence more energy is consumed, and the wireless link quality is impacted [Li et al., 2016].

In this chapter, some of the proposed and implemented works related to the targeted problem are briefly explained, the chapter include as well an illustration of the addressed problem along with the proposed solution and algorithm to prevent from failures caused by node's movement and mobility, then a simulation and performance evaluation of the implemented algorithm using the Vector-Based Forwarding protocol is described with the simulation results discussion and performance comparison.

3.1 State of the art

In this section, we presents some of the proposed researches that are aimed to overcome the problem of the link deficiency and failure which can be caused by poor link quality due to the continuous movement of the underwater sensor which results a position inaccuracy, a loss of connectivity and unreliable network, the following approaches are intended to detect and prevent from such problem cited above.

- **Communication Void Avoidance Algorithm (CVA) :** the authors [Sani et Mohamad, 2020] have proposed a mechanism to avoid void node within the network, due to the water current, mobile sensor node can easily drift away from their current location, by considering the position changing information of a sensor, a node can determines if it neighbor is void or not, the proposed method has been divided into three stages, which is first, the information collection stage, where the underwater sensor are exchanging hello messages to identify their neighbors, the information of the neighbor is stored in a Table of Neighbor Information (TNI) which includes their depth information, ID, and residual energy, if a node is concerned by a void region it will broadcast a void alert message, the nodes that receives this message alert drop immediately this sensor from their (TNI).

The second part of the method is the void avoidance stage, where the strategy employed to avoid void node makes use an Inertia Measurement Unit (IMU) to estimate the position changing, while the nodes located at the right and left the edge of the network may easily drift away from the network area, the communication void avoidance strategy maintains those nodes in a table and verify their (IMU) periodically, if any changes is detected then the node is considered as void node, sensor nodes located at the middle of the network verify by themselves their table every certain time if there is a node with no neighbor in it (TNI), then the node is considered as void and has to issue a void alert message, finally the data packet forwarding stage is processed where the residual energy of the node and it hop count of the next forwarder are taking into consideration besides the void free node to select the next forwarder. The proposed algorithm achieves an energy utilization balances and avoid void nodes as well.

- **A Localization Based Routing Protocol for Dynamic (LBDR) :** as the node float mobility is considered as the basic challenge for the UWSN, where the underwater sensor are frequently changing their current location, [Han et al., 2016] have proposed a routing protocol that combines between both aspects the localization process and routing as well, (LBDR) is mainly divided into two phases, mainly the localization stage, where the network is divided into different layers from the deep water to the surface according to water depth, and sensor nodes are categorized depending on their location, the sensor that are lying at the water surface are called original beacon nodes, those sensors can get their location using a GPS device and broadcast it in periodically manner, when the sensors lying at the first layer receives signals from the original beacons, they can locate themselves according to it, those sensors are called promoted beacon nodes, when their localization is finished, the nodes lying at the lower layers can locate themselves using the received signal from original or promoted beacon sensor nodes, the method is called hierarchical spreading localization.

  Then the routing process will begin, noted that the approach is based on the VBF routing protocol that makes use a virtual pipeline based on a vector which only sensors inside the pipe and close to the vector are allowed to forward, the authors consider that this criterion is tight for forwarder node, and includes the localization error ϵ in the forwarder selection decision, where the distance between a node and it forwarder by taking into account ϵ has to be lower than the radius of the pipeline W. Hence more node will become candidate forwarder and achieving a high throughput, whereas the data load become high on the nodes within the pipe if there is no new nodes that are bring to the pipe [Khan et al., 2018].

- **Node mobility issue :** during a packet transmission process the mobile nodes can frequently change their location, which results in improper communication, the approach proposed by [Agarwal et Rakesh, 2017] has been aimed, so that even if the nodes are changing their location, the communication in the network between the nodes can take place, for that, the area where sensor nodes are located is called sensing zone that is mapped into two dimensional space that is divided into four quadrants respectively the upper left (UL), upper right (UR), lower left (LL), and lower right (LR), the division is established for configuring and handling the mobility of the node during a packet transmission.

When a node wants to transmit a data packet through a certain path toward the destination, it has to sense the nearest intermediary node in another quadrant by computing the Euclidean distance, this intermediary node is considering as an alternative node that keeps the history of the sender node and the routing table that contains all the required information to root packet, the intermediary node has to be located in another quadrant other than the sender quadrant. The communication is always done in a cross quadrants not within the same quadrant. The approach has provided a new method that has addressed the mobility issue and defeats the temporary loss of wireless communication, by exploiting alternative paths.

- **The Fault Resilient based on (MFO) scheme :** due to the underwater environment interference, random deployment and mobility of sensors, [Kumari et al., 2020] have proposed a new mechanism called fault resilient routing based on moth flame optimization (MFO) scheme that is aimed to overcome the problem of disjoint path, link failure and data overloaded produced by the harsh marine challenges, the main purpose of this approach is to select the best forwarder sensor node to transfer the data packets to the nearest Autonomous Underwater Vehicles (AUV), that will moves the packets toward the based station, instead of using the cluster head (CH).

  Firstly, the approach virtually divides each underwater level into number of grids that represents the half of the node transmission range, and then apply other mobile nodes at the center of not covered grids, thereafter the technique consist to select the optimal sensor node to forward the packet using a novel fitness function introduced with the MFO scheme, the function makes use the link quality between the sensor nodes and the AUV with the help of the packet error rate (PER) and packet reception ratio (PRR), the residual energy of the concerned node, and the number of the connected nodes with the sensor, located within it transmission range.

  The fault resilient protocol distinguish two different routing technique based on the MFO scheme, where the first one consist to transfer the packet directly to the AUV if the autonomous device is inside it range, otherwise if the AUVs are not inside the node's range, the packet is sent through neighbor, the process makes use the list of the neighbor nodes and choose the best node according to it highest fitness value, then the selected node will transfer the packet toward it nearest AUV. The approach avoid the overburden data and the re- clustering issue, that provide a high convergence rate, a fast delivery, and energy saving.

- **Towards Robust Routing in 3-D UWSN (RRP) :** due to the uncertain node and link failure problem that leads to link breakage, [Xu et al., 2013] have proposed a new robust routing protocol (RRP) that allows sensor nodes to rebuild backup links to repair the failed links, as well as a node has the ability to enlarge it coverage area in order to build new links when the concerned path is not reachable through the created backup links.

  The (RRP) mechanism is divided into two phases, the first phase is route discovery process where each packet contains the positions of the source node, the target node, and the relay node that has transmitted the packet, when a node receives the packet it has to compute a gravity value of its neighbor nodes, and then it chooses the neighbor node with the maximal gravity value as the next relay node to forward the data packet, for that the source node will select the next relay node as per the gravity value computation and add this route to it routing table meanwhile the according backup link is constructed, the operation is iterated till the packet achieve the target node, at this point a routing path that can process the future link and node failure is setting up.

  The second phase is the route maintenance, when a sensor node transmit a HELLO packet, it has to receive the replay from the relay node as ACK packet, if the ACK is not received the link is considered as broken and the route maintenance process is evoked, however the source will first retrieves a relay node at the head of the path and forward the packet to it, the process will continue with the receiving node that will in turn retrieve a node at the head of it routing path if the current does not receive any reply from it relay node, it will consider that the link is broken, a backup link with another relay node is then constructed, this new relay node consider that the previous node with which the link was broken is not in it routing table, so the node enlarges it coverage area to attempt this node and add it to it routing table, the new selecting relay node will continue forwarding the recover data packet. (RRP) reduces the link and node failure in efficient manner in terms of minimum network delay, successful delivery packet, and energy consumption [Tuna, 2018].

3.2 Proposed approach for detection and prevention from link interruption and failure problem

In this section, we describe the problem discussed for our contribution, by determining the main issue addressed in this scope, we propose then our solution that is aimed to overcome the targeted problem and provide an enhancement to recover from the addressed issue.

3.2.1 The Predictive Threshold Zone PZ_{TH}

In our contribution, according to the VBF functionalities, before that a sensor node can be selected as the new forwarder and continue it forwarding process inside the pipeline, the link with the concerned sensor node has to be evaluated to ensure if the link will be maintained during the transmission process, for that, the main purpose is to compute an interpolate predicted signal value received at the concerned sensor node $P_{(tpt)}$ and by comparing this measured value to a predefined received signal strength threshold RSS_{TH} , in order to ensure the link reliability between the sender and the receiver node. To minimize the interpolation computation, we defined a certain virtual area inside any transmission range of a sender, called PZ_{TH} to make sure that only nodes laying within this area will evaluate their link quality with the previous sender. Before that a node can be selected as forwarder, it predict signal value $P_{(tPT)}$ has to be computed according to three input parameters.

Those parameters have to be retrieved from data frames information (Receiving power signal strength RSS_i and their according Time T_i), and compared to RSS_{TH}. In order to reduce the computation process of P_{tPT} we defined an area within the transmission range of the sender node called predictive threshold zone PZ_{TH} as it is shown on Figure 3.1 , the goal is that to ensure that only nodes inside this zone has to compute it predict signal value and compared to the RSS_{TH}, to make sure if a link interruption can occur or not, by measuring the link efficiency. The calculation of the PZ_{TH} is described as follow :

Following the basic VBF, the valid range of the routing pipeline is $[0; Tr_{distance}]$ where $Tr_{distance}$ represents the pipeline diameter[Nicolaou et al., 2007] moreover the valid range of a node is same as the pipeline, where it transmission range value R is $[0; Tr_{distance}/2]$ The PZ_{TH} is defined in such a way to allow the reception of three consecutive data frames at the receiver node x where $PZ_{TH} = \alpha$ hence the allowed valid range for a node is $[0; D_{TH}]$, where $D_{TH} = Tr_{distance} - 2 * PZ_{TH}$, and it transmission range R_N is $[0; R_N]$, where $R_N = R - PZ_{TH}$.

3.2.2 Problem description

Since the UWSN are widely and randomly deployed and dispersed in a three dimensional space (X,Y,Z)[Hossain et al., 2016] due to the greatness of the oceans and marine environment, the Underwater sensors are facing several challenges and limits [Zenia et al., 2016], among the multiple issues encountering by the underwater acoustic sensors, we have been interested on the link failure and interruption issue caused by the mobility and movement of sensors in a major time, as the sensors can frequently change their positions due to their frequent mobility affecting the network topology and performance. However, during a data packet transmission a node may drift away from it sender or forwarder range which results in a link breakage between the sensors, meanwhile numerous data packet are lost, in addition the mobility promotes the creation of void region, where there is not path leading to the attended destination. Numerous problems can arise and submerged due to the node's movement, according to the Figure 3.1, S is the source node or forwarder, the nodes A and B are the receiver and next forwarder, considering the following problem statements :

- The node A is the receiver of the node S and can be elected as the next forwarder, however according to the Figure 3.1 the node is probably moving far from the node S, which makes the received signal strength decreasing generated a high amount of packet loss and large delay time, a future probability of link breakage is considered.
- Meanwhile the node A could simply move inside the range and regain it previous location position, pursuing data packet forwarding.
- Both nodes A and B could move far leaving the transmission range of the sender S quite empty, this is called a void regions, hence the node S may probably lost energy while sending packet in a void zone.

As among the weaknesses of VBF, the protocol does not takes into consideration the link reliability with it receiver before sending it data, the data packet that have been lost due to interruption are not re-transmitted by the protocol. In order to provide a mechanism that is aimed to detect probability of future interruption and to distinguish between both situations, either the node A quit the range of S or remain inside, we have proposed a new method that is aimed to clarify the current situation of the concerned node. The proposed approach defines a predictive zone called PZ_{TH} as it is shown on the Figure 3.1, which indicates that the sensor A may have a probability for a future movement outside the range, moreover the proposed study recover the lost file, by selecting a new forwarder candidate node to replace the concerned node where the range of the sender S could contains no node (void region).

Based on the Lagrange Interpolation polynomial, the formula is used to computes the received predict signal value at t time according to n input parameters, to evaluate the link efficiency before that a node is selected as forwarder. By considering the source node S, and the next forwarder node A and from the Figure 3.1 We defined the following notations :

- $d(A, S)$ is the distance between S and A.
- $Tr_{distance}$ is the transmission range for VBF.
- PZ_{TH} is the predefined threshold zone.
- D_{TH} is the allowed transmission range for the approach.
- $\overrightarrow{TS}$ the vector of the routing pipeline.
- P is the projection of the node A to the routing vector $\overrightarrow{TS}$.

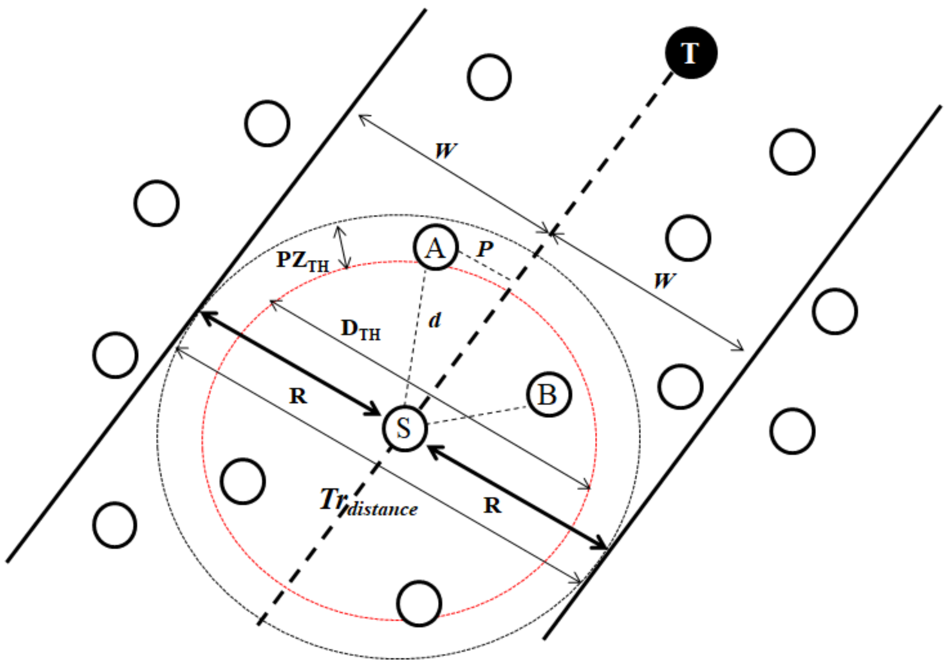

Figure 3.1 – *Problem description*

- RSS_A is the received acoustic signals strength at node A according to $l = d(A, S)$ calculated as follow :

$$RSS_A = \frac{Tr_{power}}{A(d(A,S), f)} \tag{3.1}$$

  Where Tr_{power} is the initial transmitted signal power.

- $P_{(t_{PT}}$ is the predicted acoustic signal strength value according to $RSS_{A(i)}$ calculated with Lagrange Interpolation polynomial at t_{PT}

- t_{pt} is the predict time.

- RSS_{TH} is the received acoustic signal strength threshold (the required amount of signal to receive a data packet), according to PZ_{TH}, computed with the Equation (3.1).

In our method we compute the predicted signal value $P_{(tpt)}$ at t_{PT} for a node x using the Lagrange Interpolation calculation formula according to three consecutive receiving signal strength RSS of packets from the same sender node with their respectively receiving times. As the Figure 3.2. Shows, once the node A is located at the PZ_{TH}, where $D_{TH} \leq d(A, S) \leq R$ the predicted signal value $P_{(tpt)}$ is calculated at the prediction phase. A link failure between A and S is detected if $P_{(tpt)}$ at the node A is less than RSS_{TH}, otherwise the node can continue it forwarding process.

3.2.3 Proposed solution

As VBF does not takes into account the link reliability between sender and receiver before any transmission, the sender node can keeps sending to a node that could probably fail soon. In this section we have proposed an enhancement of VBF in a cross-layer mechanism, an interaction between the Medium Access Layer (MAC) and the Network Layer, to evaluate the link quality at a receiver node x and prevent from link problems that may occurs due to the frequent change of sensor's position. The method verify the effectiveness of the link once a data frame is received at the MAC layer, and clarify if the sensor is moving outside and get far from the source, or it can simply regain to it last position or near the sender, this information will be sent to the upper layer, in such a way that before any node may be elected as the next forwarder, the information sent by the MAC layer is taken into consideration for the forwarder selection process.

Moreover, we know previously that in VBF there is no re-transmission for packet loss, in our method once the node is regarded as unreachable node, and at this time there is no sensors in its neighborhood that could be elected as forwarder, we brought a new mechanism to rediscover a new forwarder node able to forward the lost data packets, causes by the previous one. Our approach is mainly divided into three phases, the determination phase, the prediction phase and the rediscovery phase. The notations used in the proposed approach are described in the following table :

Table 3.1 – *Notation used in the proposed algorithm*

Notation	Meaning
Pkt	Packet
$Trans_{time}$	Transmission time of the packet, where i ∈ [1;3]
$Recv_{time}$	Receive time of the packet, where i ∈ [1;3]
RSS_i	Receive signal of the packet, where i ∈ [1;3]
Node_ID	ID of the concerned node
Sender_ID	ID of the sender node
LI	Lagrange Interpolation polynomial
A_{ID}	ID of the node A (MAC layer)
S_ID	The source of the concerned node (MAC layer)
SRC_ID	ID of the source of the packet (Network layer)
FD_{ID}	ID of the forwarder of the packet (Network layer)
Nb_Neighbors(S)	Number of neighbors sending same packet
F_{DIS}	FORWARDER DISCOVERY packet
S_{F_DIS}	Sender of the FORWARDER DISCOVERY packet
New_FD	New selected forwarder node
$T_{adaptation}$	The delay time of the Self-adaptation algorithm
S_{DATA_REQ}	The source of the DATA REQUEST packet

1. **Determination phase :** first of all, when a node receives a data frame it has to determine if it belongs to the routing pipeline, for that, it will computes it orthogonal projection distance with the vector d(A,$\overrightarrow{TS}$), where T is the target and S is the original source, by given the coordinates of A (x_A, y_A, z_A), T (x_T, y_T, z_T), and S (x_S, y_S, z_S) and $\overrightarrow{TA}$ the vector formed by the target and the node A .
   The orthogonal projection of $\overrightarrow{TA}$ to the vector $\overrightarrow{TS}$ is determined as follow :

$$\overrightarrow{TA}_{\overrightarrow{TS}} = \frac{\overrightarrow{TA}\overrightarrow{TS}}{\|\overrightarrow{TS}\|^2}\overrightarrow{TS} \tag{3.2}$$

   Where

$$\overrightarrow{TS} = \begin{cases} x_S - x_T \\ y_S - y_T \\ z_S - z_T \end{cases} \quad \overrightarrow{TA} = \begin{cases} x_A - x_T \\ y_A - y_T \\ z_A - z_T \end{cases} \quad \overrightarrow{TA'} = \begin{cases} x_{A'} - x_A \\ y_{A'} - y_A \\ z_{A'} - z_A \end{cases} \tag{3.3}$$

After the computation of the A projection, the coordinates of A′ are : A′($x_{A'}$,$y_{A'}$,$z_{A'}$), notice that A′ belongs to $\overrightarrow{TS}$ the distance $d(A, A')$ is then defined with the Euclidean formula distance as follow:

$$d(A, A') = \sqrt{(x_{A'} - x_A)^2 + (y_{A'} - y_A)^2 + (z_{A'} - z_A)^2} \tag{3.4}$$

The distance $d(A, \overrightarrow{TS})$ is compared with the using radius 'W' value of the pipeline if d ≤ W, the node belongs to the routing pipeline, then it distance with the source node d(A,F) is calculated using the Euclidean distance described above and compared with D_{TH}. If $d(A, F)$ is high than D_{TH} and less than the transmission distance range as follow : $D_{TH} \leq d(A, F) \leq \text{Tr}_{distance}$, then the node A is within the Prediction Zone A $\in \text{PZ}_{TH}$ a probability of a future link failure is expected. Once the node A is located at the PZ_{TH}, there is a probability of a future link failure the link quality has to be evaluated, in this case the prediction phase is processed. Else if *d(A,S)* is less than D_{TH} : *d(A,S)* $\leq \text{D}_{TH}$, the node will simply continue it forwarding process.

Algorithm 1 Determination phase

Step 1 : Node A receives Pkt_i from S or F;
Step 2 : Calculate $Projection(A)$;
Step 3 : Get the coordinate $(x, y, z)_{A'}$ after Projection(A);
Step 4 : Calculate d(A,A′);
if $d(A, A') \leq W$ **then**
  Calculate $d(A, S)$
  if D_TH $\leq d(A, S)$&$d(A, S) \leq Tr_{distance}$ **then**
    Get($Trans_{time(1)}$,RSS_1)
    i := number_received_pkt
    while i $\leq$ 3 **do**
      ResetTransStatus(S)
      Get ($Trans_{time(i)}$,RSS_i)
      $\text{Recv}_{time(i)} := Trans_{time(i)} + \frac{d(A,S)}{v_0}$
    end while
    Delete(Pkt_i)
  end if
  Initiate Prediction phase
end if

2. **Prediction phase :** when the node A is located at the PZ_{TH}, at this time there is a probability that the link between A and S may interrupt, the node A is moving out the sender range, or the node can simply regains it old position or become near the sender, to clarify those situations, three consecutive received data frame information (Received Power Signal Strength RSS and their according received Time) from the same source S to the node A are take into consideration. As VBF has limited 2 received packets per a second, hence, if the number of data frame received by node A from sender S is 2, the first and the second received signal strength by the node A are collected according to their respective times, in this case the sender S will reset it transmission status and resend again a copy of the last data frame after a certain time defined as follow :

$$T_{time3} = Current_{time_3} + Delay \tag{3.5}$$

to avoid any collision problem. The data frame is now received by node A the third received signal strength according to it time is collected. In other case, if the received data frame from S to A was limited at 1, the sender S will reset it transmission status and resend 2 copy of the last data frame separated by a certain time of period.

$$T_{time_2} = Current_{time2} + Delay \tag{3.6}$$

$$T_{time_3} = Current_{time3} + Delay \times 2 \tag{3.7}$$

Since VBF has limited two received packets per a second, hence the approach creates a third copy of the last frame and resend it to the concerned destination, in order to gather three consecutive information packets, within a certain time interval $T[t_1; t_3]$, the RSS_i and their received Times T_i are retrieved where I ∈ [1;3]. The additives packets will be obviously dropped once the RSS and the time T are retains, to avoid any collisions problems. The received data Frame time is calculated as follow :

$$T_i = Transtime_i + \frac{d(A,S)}{v_0} / i \in [1;3], v_0 = 1500m/s \tag{3.8}$$

Lagrange Interpolation Polynomial : the Interpolation polynomial gives an estimation according to 'n' input parameters at x value, the general equation is given by :

$$P_n = \sum_{k=0}^{n} l_k(x) f(x_k) \tag{3.9}$$

Where l_k are polynomials of degree n that form a basis of P_n.

$$l_k(x) = \prod_{i=0, i \neq k}^{n} \frac{x - x_i}{x_k - x_i} \tag{3.10}$$

In our study, the estimation or predict value is given according to three received signal strength, hence a polynomial defined explicitly of a degree n=3, where $x_i = t_i$ and f(x_k) = RSS_i, x is the predict time :

$$\begin{aligned} P(x) = {} & \frac{(x-t_2)(x-t_3)}{(t_1-t_2)(t_1-t_3)} RSS_1 + \frac{(x-t_1)(x-t_3)}{(t_2-t_1)(t_2-t_3)} RSS_2 \\ & + \frac{(x-t_1)(x-t_2)}{(t_3-t_1)(t_3-t_2)} RSS_3 \end{aligned} \tag{3.11}$$

where the predict time $t_{pt} = t3 + M_t$, and M_t is the average value of the measurement[Boukli-Hacene et al., 2014] calculated as follow :

$$M_t = t_3 - \frac{t_1 + t_2 + t_3}{3} \tag{3.12}$$

Once the interpolate value $P_{(tpt)}$ is computed it has to be compared with a Threshold Receiving Signal Strength RSS_{TH} given in the Equation (5) previously cited, if ($P_{(tpt)} < RSS_{TH}$) and the first received signal strength is high than the second, and the second is high than the third as follow : ($RSS_1 > RSS_2 and RSS_2 > RSS_3$) the node A is moving out the range and the received signal by A is too weak to be attempt, a high possibility of a link failure is predicted, in this case the node A can not be elected as forwarder for node S. We use the same variable as the approach of detection using Newton Interpolation an "xmit reason" variable to prevent the network layer about the link efficiency, this variable will take a value of "XMIT REASON LOW RSS", in a case where the received signal is low, indicating the "Node ID" concerned and it "Sender ID" to the upper layer. Otherwise "xmit reason" will take a value of "XMIT REASON HIGH RSS", which means that the receiving signal is good enough and the node A can continue it forwarding process and no link failure is taking place.

Algorithm 2 Prediction phase

```
Step 1 : Calculate LI(Recv_time(i),RSS_i);
if LI ≤ RSS_TH & RSS_1 > RSS_2 & RSS_2 > RSS_3 then
    xmit_reason := XMIT_REASON_LOW_RSS
    Node_ID := A_ID
    Sender_ID := S_ID
else
    xmit_reason := XMIT_REASON_HIGH_RSS
end if
```

3. **Rediscovering phase :** in the basic VBF, when a node receives a packet pkt, it will determine if it is close to the routing vector and within the pipeline, if so the node will forward the data packet carrying it coordinates in the FP field, after a certain time interval $T_{adaptation}$ based on it desirableness factor. In this proposed protocol the forwarder selection policy is redefined in such a way that, when a node receives a packet it has to check if it is eligible to forward and in addition it "xmit reason" value. If the variable has taken the value of "XMIT REASON HIGH RSS" , the node will simply continue it forwarding process. Otherwise if the variable has taken the value of "XMIT REASON LOW RSS", the node check if it is the concerned node , according to the previous sending node "Sender ID" that has sent pkt, this process permit to distinguish from other pkt that has been received from other nodes.

   Once this condition is verified, the sender of this concerned node check if the number of all neighbors to which it sends the pkt including node A is more than 1, if so than many nodes can be elected as forwarder, otherwise if the number is equal to 1, it means that A was the only available node before the interruption of the link, in this case, the sender S will broadcast a "FORWARDER DISCOVERY" packet to request another potential available forwarder in it range, in order to prevent from data packets lost, if there is any node except node A inside it range and close to the vector it will reply by a "DATA REQ" packet, the sender S can now re-transmit the DATA packet to this new forwarder.

   - **FORWARDER DISCOVERY :** once a node receives the "F DIS" packet it will determines the following information :
     - If it is close to the routing vector $Proj_{NodeID} \leq W$ and inside the pipeline.
     - If the available node is not inside the PZ_{TH} zone.
     - If it is not the concerned node by the prediction phase.
   - **DATA REQ :** when the above conditions are satisfied then the node will reply with "DATA REQ" to the sending source node of "FORWARDER DISCOVERY" requesting data packets DATA. Once the source node receive the "DATA REQ" it will reply with a data packet "DATA" to the sender of "DATA REQ" node that will be selected as the new forwarder node, and continue the forwarding process with the receiving data. Notes that each cited sending packets are transmitted in a certain time delay calculated by the $T_{adaptation}$.

Algorithm 3 Rediscovering phase

```
Step 1 : Get DATA Pkt
Step 2 : Check if A is close to the Routing Vector
if Close(A) then
  if xmit_reason = XMIT_REASON_LOW_RSS then
    if Node_ID = A & Sender_ID = $SRC\_ID$ or Sender_ID = FD_ID then
      Get Nb_Neighbors(S);
      if Nb_Neighbors(S) = 1 then
        Prepare F_DIS Pkt
        Calculate Desirableness(S)
        Calculate Delay $T_{adaptation}$
        Broadcast F_DIS Pkt
      else
        Free DATA Pkt
      end if
    else
      Calculate Desirableness(A)
      Calculate Delay $T_{adaptation}$
      Relay (Pkt)
    end if
  else
    Free DATA Pkt
  end if
end if
Step 3 : Get F_DIS Pkt
if (Node_ID $\neq$ A & Close(Node_ID) & d(Node_ID,$S_{F\_DIS}$) $\leq D_{TH}$) then
  New_FD := Node_ID
  Prepare DATA_REQ Pkt
  Calculate Desirableness(New_FD)
  Calculate Delay $T_{adaptation}$
  Send DATA_REQ Pkt
else
  Free F_DIS
end if
Step 4 : Get DATA_REQ Pkt
if Node_ID = S_ID & $S_{DATA\_REQ}\_ID$ = New_FD then
  Prepare DATA Pkt
  Calculate Desirableness(S_ID)
  Calculate Delay $T_{adaptation}$
  Send DATA Pkt to New_FD
else
  Free DATA_REQ;
end if
```

The Figure 3.2 and Figure 3.3 illustrates the proposed algorithm for CLPP-VBF.

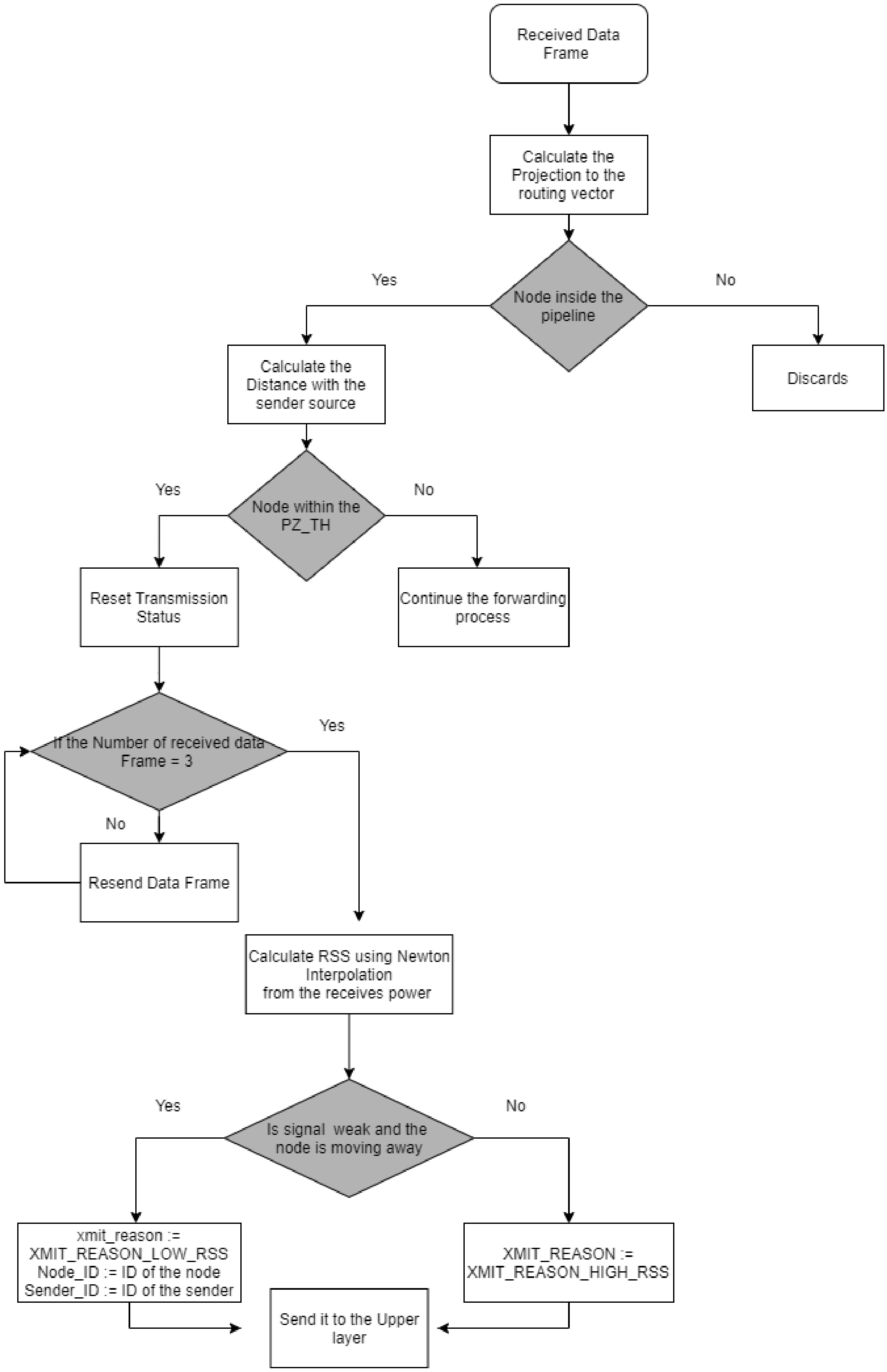

Figure 3.2 – *Process of the Determination and Prediction phase*

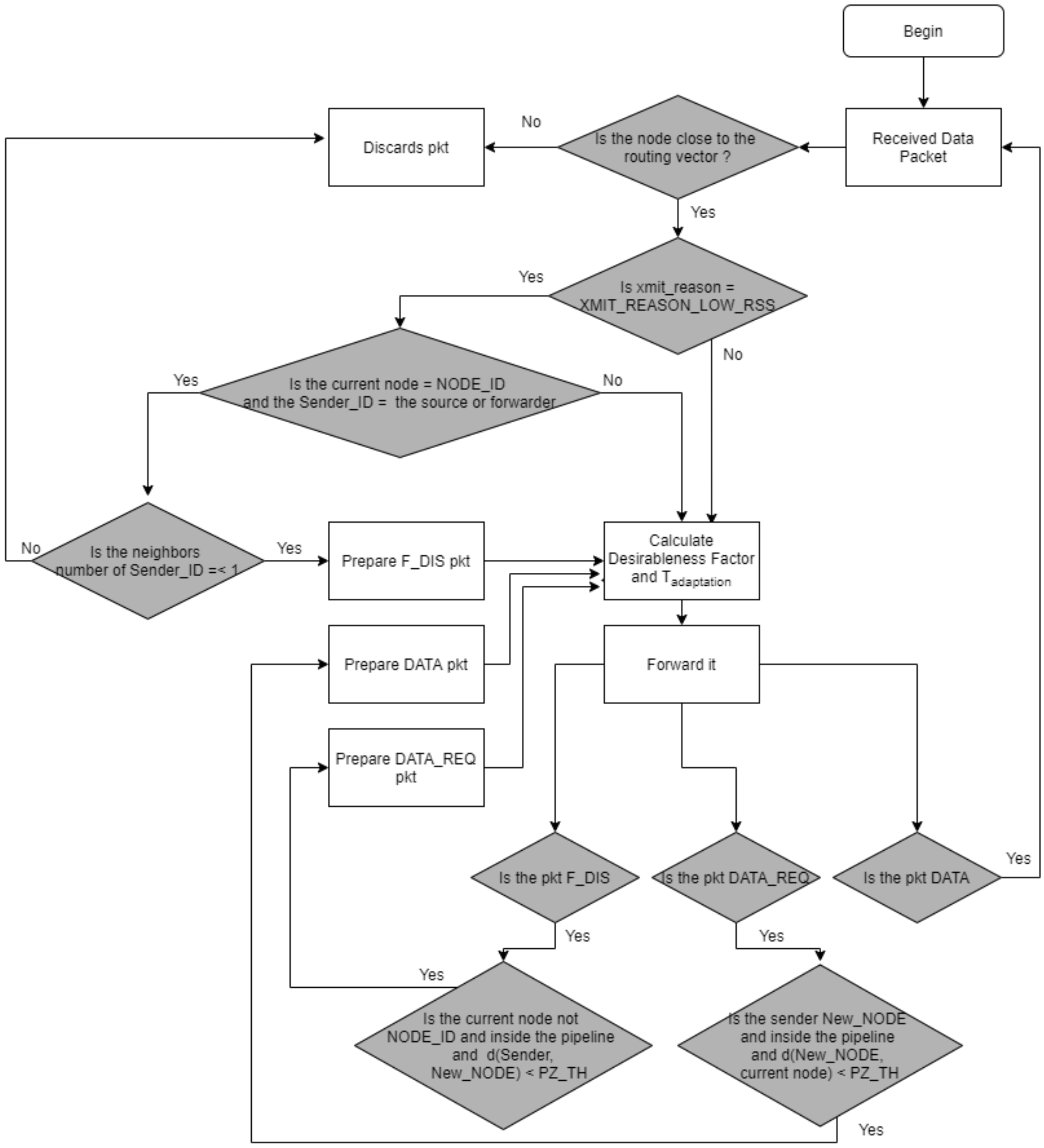

Figure 3.3 – *Process of the Rediscovering phase*

3.3 Simulation and performance evaluation

In this section, we presents the set of the simulation parameters used for the evaluation of our approaches, then we give an extensive explanation about the evaluated results according to the metrics addressed for this work. We used the notation CLPP-VBF for our contribution.

3.3.1 Simulation environment

The used simulation environment is represented in the following table : We use a three-dimensional space (1000 mx 1000 m x1000 m), the Source S and the target T are fixed at (1000,0,0) (0,1000,1000) respectively, the nodes are randomly deployed, the Radius of the pipeline is varied W = 100,200, The Range = 100 meters, we varied number of nodes from (100 to 500) , the maximum speed of node is varied S= 3m/s,6m/s their initial energy E_0 is 10000 j, the packet size is 50 Bytes, the number of received packets is 2 per second,
the transmission of acoustic signal power is set at 0.2818 Hertz, the frequency is 25 Khz the simulation time is 200 seconds, the MAC layer bit rate is set at 10 Kbps.

Table 3.2 – *Simulation parameter used for CLPP-VBF*

Simulation Parameter	Value for CLPP-VBF
Deployment area	(1000 m x 1000 m x 1000 m)
Network topology	Random grid
Number of nodes	(100,200,300,400,500)
Routing protocol	VBF, CLPP-VBF
Radius	100 m , 200 m
Range	100 m
Node speed	3 m/s, 6 m/s
Initial energy	10000 j
Packet size	50 Bytes
Number of packet	2 Packet / sec
Frequency	25 Khz
MAC protocol	UnderwaterMAC
MAC layer bit rate	10 Kbps
Communication medium	Acoustic waves
Speed of sound	1500 m /s

3.3.2 Performance metrics

We evaluate the performance of our proposed approach against the basic VBF using the following metrics: The Packet Delivery Ratio, Average End to End Delay, Energy Consumption and Energy Efficiency.

1. **The Packet Delivery Ratio (PDR) :** is a metric that gives the ratio of the number of the delivered data packets at sink node, according to the number of sending data packets by the source :
$$PDR = \frac{\sum Received_{Packets}}{\sum Sending_{Packets}} \times 100 \tag{3.13}$$

2. **The Average End to End Delay (AE2ED) :** represents the average time needed to ensure the data packets reach the destination (Sink).
$$AE2ED = \frac{\sum R_{time(i)} - \sum T_{time(i)}}{\sum Received_{Packets}} \tag{3.14}$$
Where $T_{time(i)}$ is transmission time of the packets, and $R_{time(i)}$ is the received time.

3. **The Energy Consumption (EC) :** illustrates the total difference between the initial energy E_0 and the residual energy E_r of sensor nodes
$$EC = \sum(E_0 - E_r) \tag{3.15}$$

4. **The Energy Efficiency (EE) :** which is successful delivery of data at the sink node with the amount of energy consumed in the network [Ketshabetswe et al., 2019]:
$$EE = \frac{successrate \times totalpacketsenttothesink}{totalenergyconsumed} \tag{3.16}$$

3.3.3 Result discussion

The following result represents the detection and prevention approach based on the Lagrange Interpolation in a cross-layer manner, we simulated with two different radius 'W' value 100m and 200m, and varied the speed of the node at 3m/s and 6m/s in order to clarify the impact of the node speed, and discussed the simulation results according to the three respective metrics Packet Delivery Ratio, Average End to End Delay and Energy Consumption.

1. **Packet Delivery Ratio**

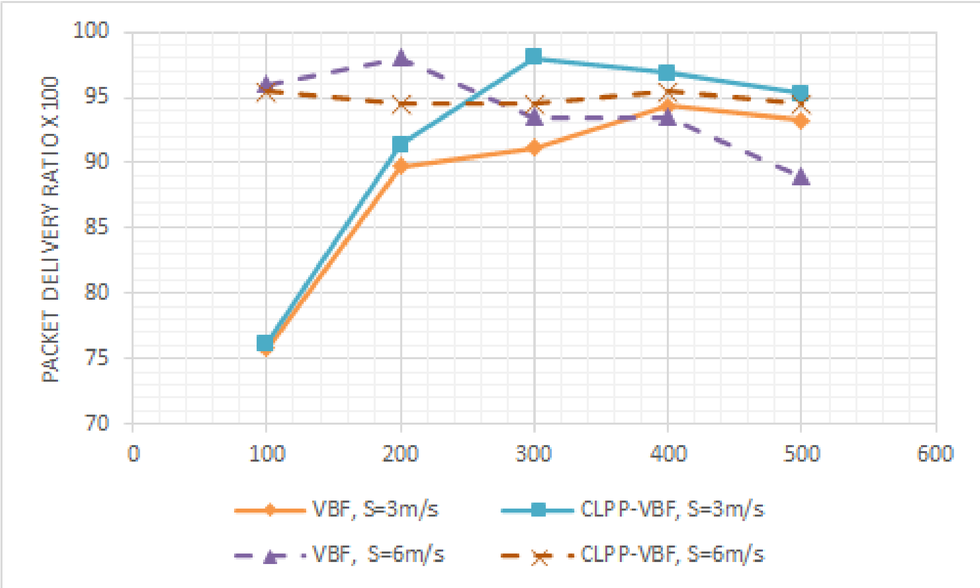

Figure 3.4 – *Packet Delivery Ratio W=100m*

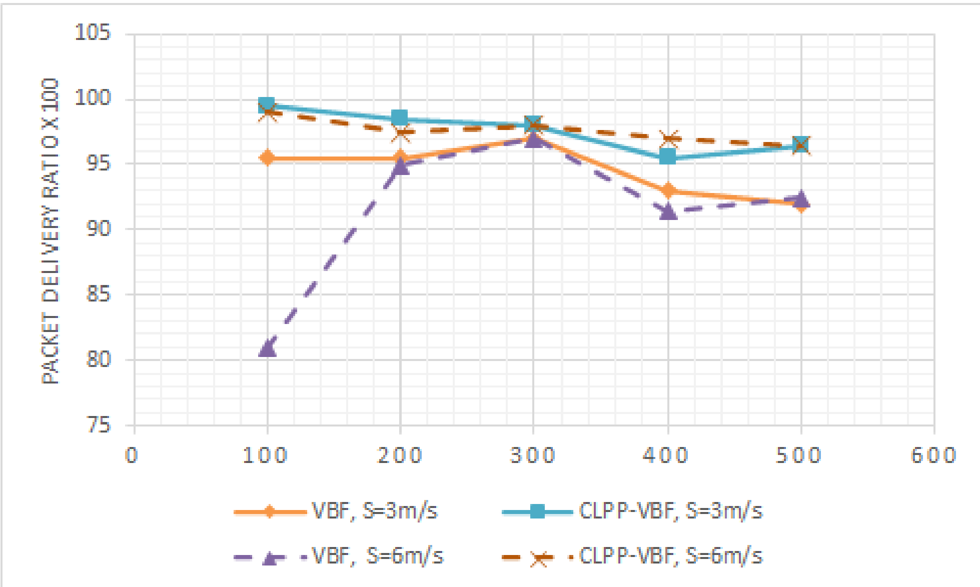

Figure 3.5 – *Packet Delivery Ratio W=200m*

The Figure 3.4 and Figure 3.5 shows the results of the comparison study between VBF and CLPP-VBF in term of packet delivery ratio, and as we can observe from both figures, as large as the network density is, the PDR increases, and this is due to the fact that more the density is, more there is nodes within pipeline that will forward data packets. From both figures. The results of VBF over CLPP-VBF at speed = 0-6 m/s, shows a large amount of PDR at scenario '100' with at low density of nodes, as opposed to the ones with speed = 0-3 m/s, this goes to the fact that when the speed is highest the chance to create more paths all over the pipeline raises, nodes outside pipeline can move faster and became near the vector.

In other hand, from Figure 3.5 At W=200 and speed=3m/s, the delivered ratio has attempted a high amount of PDR compared to results shown on Figure 3.4, and this goes to the fact when the radius pipeline became larger, the low speed of nodes does not affect, for the reason that more there will be nodes involved in the forwarding process, more the PDR increases, and in the case of smaller radius pipeline, the involved nodes inside became less even if the network is dense. We conclude that the radius pipeline has a large impact on PDR despite the low speed of nodes.

By comparing the both schemes we can see that the performance of the basic VBF has been reduced with a high speed as it is shown on both figures, this can be explained by the fact that more the node became faster, the probability of link failure raised, as it was explained previously, although that VBF does not takes into account the link quality before any forwarder selection, it performances have been decreased compared to scheme with low speed. CLPP-VBF has provided a new mechanism to overcome the link failure problems, by selecting forwarders with an effective link quality, and re-transmit data packets to other neighborhood nodes, in case of link interruption with a receiver. We conclude that CLPP-VBF outperforms the VBF in term of PDR, at different speed level and radius measure.

2. **Average End to End Delay**

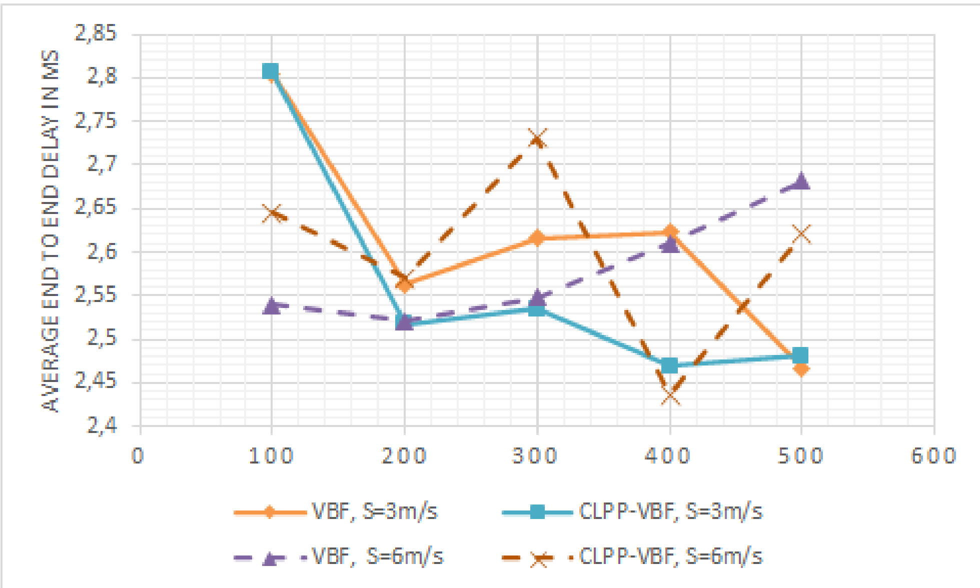

Figure 3.6 – *Average End to End Delay W=100m*

The Figure 3.6 and Figure 3.7, indicates the results of the comparison study between VBF and CLPP-VBF in term of Average End to End Delay. From Figure 3.6 The scenario for both scheme VBF and CLPP-VBF at speed = 3m/s, demonstrates a reduction of the end-to-end delay when the network became larger, this goes back to the fact that the basic VBF gives the priority to the most desirable node with a less desirableness factor value (near

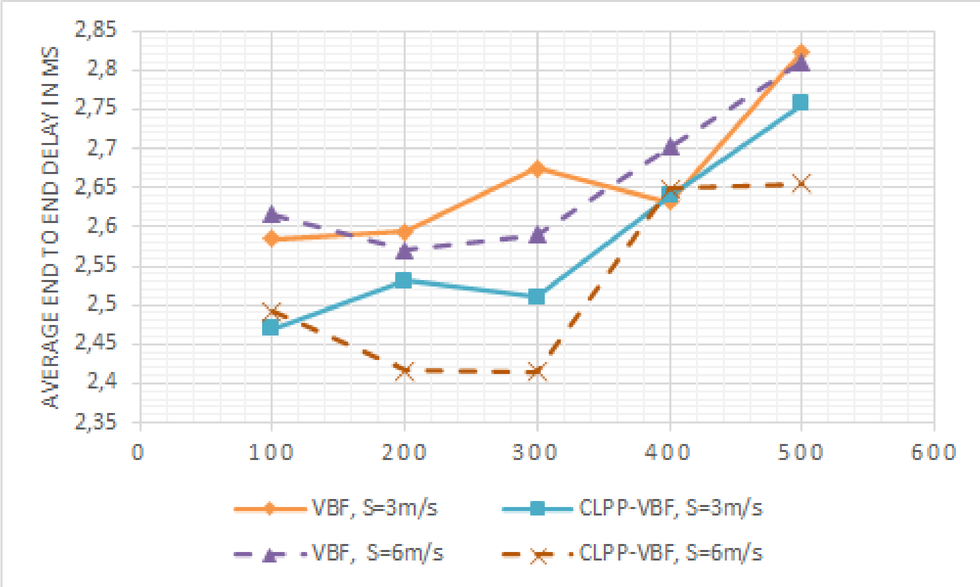

Figure 3.7 – *Average End to End Delay W=200m*

to the vector) to forward data packet, and a less time to wait, this can reduces the AE2ED, and in another hand a node with high desirableness factor value (far from the vector) has much time to wait, this generates a highest delay. When the network is densely deployed, there could be more nodes inside pipeline, it means that there is more than one possible path, hence the delay time decreased, meanwhile at a level speed = 6m/s the delay has raised at some scenarios, we conclude that the mobility of nodes can affects the network performance in term of AE2ED when the involved nodes are less (W=100), where the nodes can moves easily outside pipeline and creates shadow zone (a node with no path leading to the sink), this has raised the delay time, while some of them can returns inside the pipeline and reduces the delay time.

Moreover, from the results represented in Figure 3.7 As we can see from the results, the amount of AE2ED is increasing compared with the Figure 3.6, and this is for the reason that when the radius became larger the distance between nodes and vector can be large, this can generates a highest desirableness factor, that gives a long time to wait. From both level speed we can observe that when the speed = 6m/s the time to wait became less than the results at speed level = 3m/s, and this goes back to the fact that when nodes are moving faster, they could get closer to the vector, and this will reduce the delay time according to the self-adaptation algorithm policy. We can conclude that a large speed has an impact over the AE2ED with a smaller radius pipeline, otherwise a large radius can affect the delay time with a low speed level.

CLPP-VBF outperforms VBF in scenarios W = 100, S=3m/s and W=200, S=3m/s and S=6m/s, for it purpose to avoid forwarder selection that can moves outside the range generating a high average delay and switch to another available node, the scenario W=100, S=6m/s shows a low demerit for the reason that the lowest involved nodes within pipeline can move outside the pipe due to the highest level of speed, Despite that, CLPP-VBF has provided a better performance in a large network.

3. **Energy Consumption**

The Figure 3.8 and Figure 3.9, indicates the results of the comparison study between VBF and CLPP-VBF in term of Energy Consumption. As we can see in both figures,

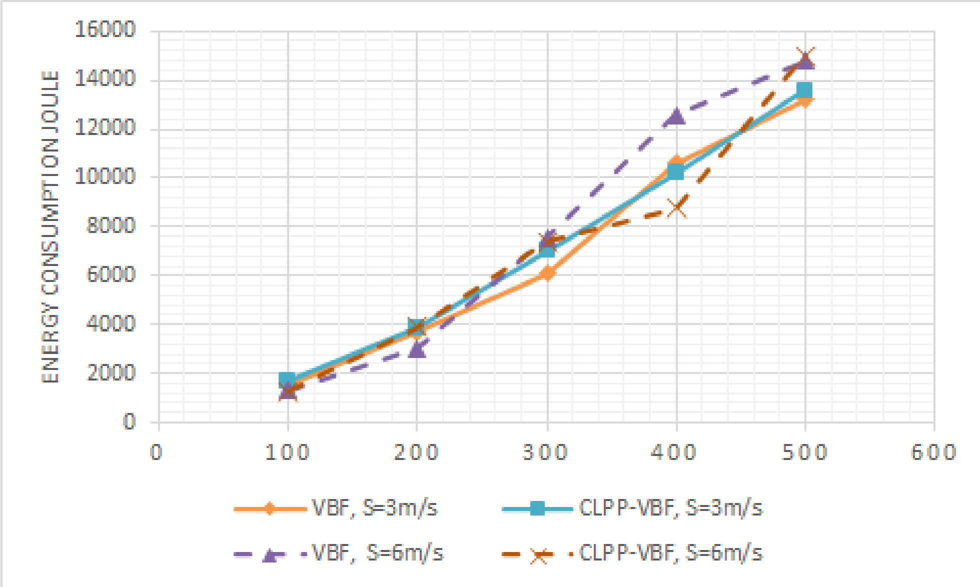

Figure 3.8 – *Energy Consumption W=100m*

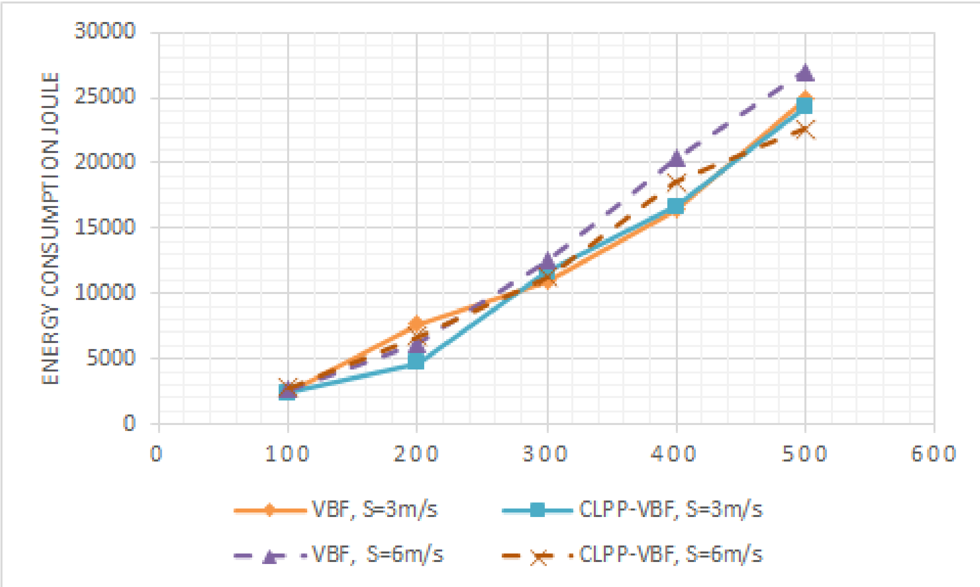

Figure 3.9 – *Energy Consumption W=200m*

the consumed energy for the CLPP-VBF at speed =3m/s has slightly raised at scenario '300', this is due to the additives sending packet at rediscovery phase to find and select another available node which can be elected as forwarder in a case that if the concerned node by the interruption is the only one at the sender's range, but in another scenario when the speed level = 6m/s we can observe that the consumed energy is high for the VBF than CLPP-VBF, this goes back to the reason that when nodes are faster, they can be easily moves inside and outside the pipeline, this will involves much better nodes to the forwarding process generating an energy depletion, whereas in CLPP-VBF, our mechanism avoid unnecessary forwarder selection that may moves out the range due to their mobility, this has reduced the consumed energy despite the speed level.

The Figure 3.10 and Figure 3.11, illustrates the energy consumption results of the two

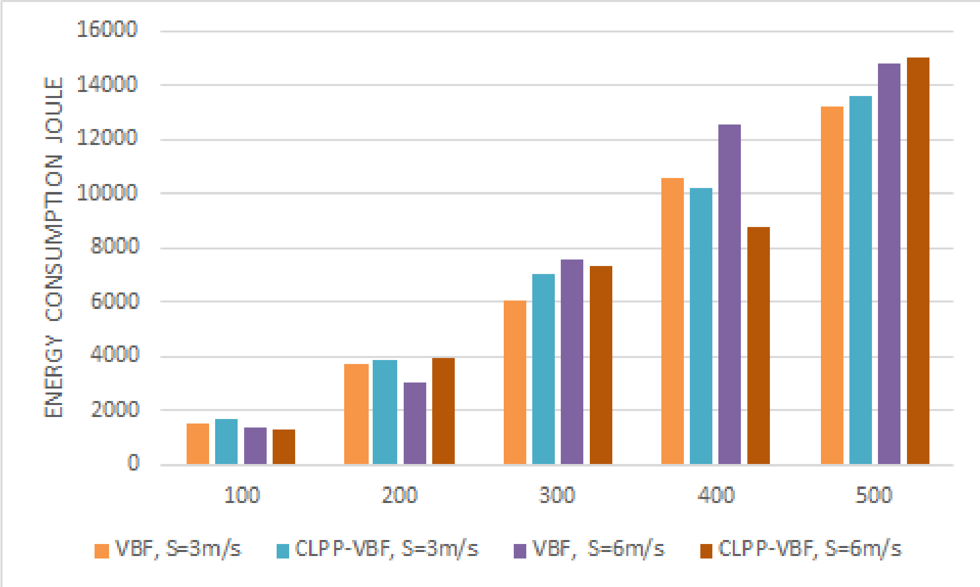

Figure 3.10 – *Energy Consumption W=100m*

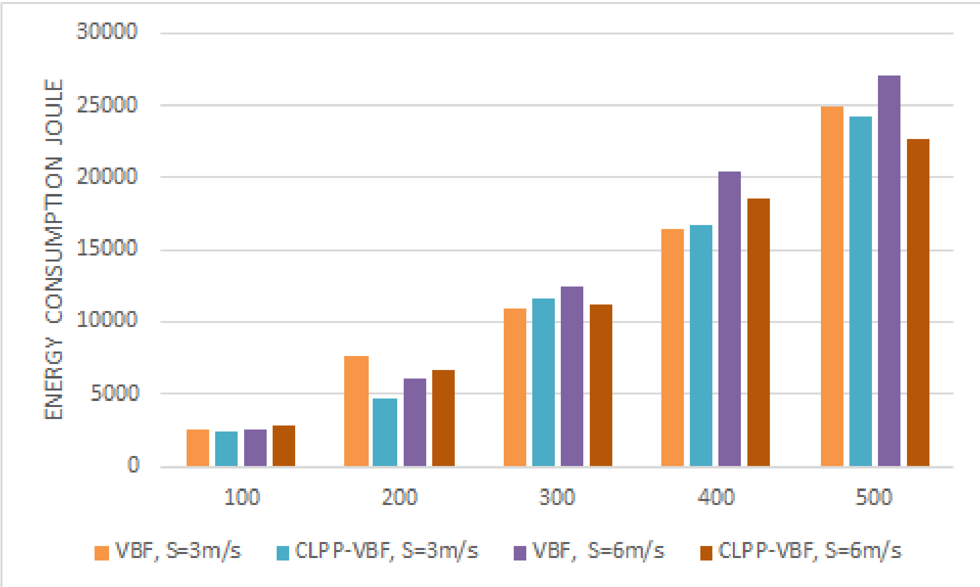

Figure 3.11 – *Energy Consumption W=200m*

figures 3.8 and 3.9 respectively, for both scenarios with the radius W=100 and W=200, we can conclude that the CLPP-VBF outperforms the VBF in term of energy consumption metric at a high speed level 6m/s, the overall consumed energy at 3m/s for both routing protocol are nearly the same.

4. **Energy Efficiency**

   The energy efficiency metric is affected by the successful delivered data and the consumed energy, where the metric bring good results where the success rate is more than the consumed energy, where PDR is large as same as the EC the metric is affected, moreover a low success rate with a large consumed energy bring a low energy efficiency as well.

   As it is shown on the Figure 3.12 and Figure 3.13, the Energy Efficiency is presented according to the nodes number at different speed value = 3 m/s and 6 m/s, VBF and

CLPP-VBF are approximately in most of scenarios, CLPP-VBF has consumed a slightly more energy for the reason that the protocol adopt a mechanism to select a new candidate node if the previous node was concerned by the link failure, that may generates more consumed energy, since a new forwarder is involved, that raise the successful achieved data packet, however the energy efficiency is affected.

In some scenarios despite the density of the network the pipeline may contains void regions as the sensor nodes are frequently moving out and inside the pipeline, which may results in a low success rate with a medium energy consumed, hence the energy efficiency is affected, in other hand, a large delivered data packet may not involved many sensors, since the presents nodes inside pipeline that are forwarding packet are few this may generates a good data rate with a low energy consumed, thus improves the energy efficiency.

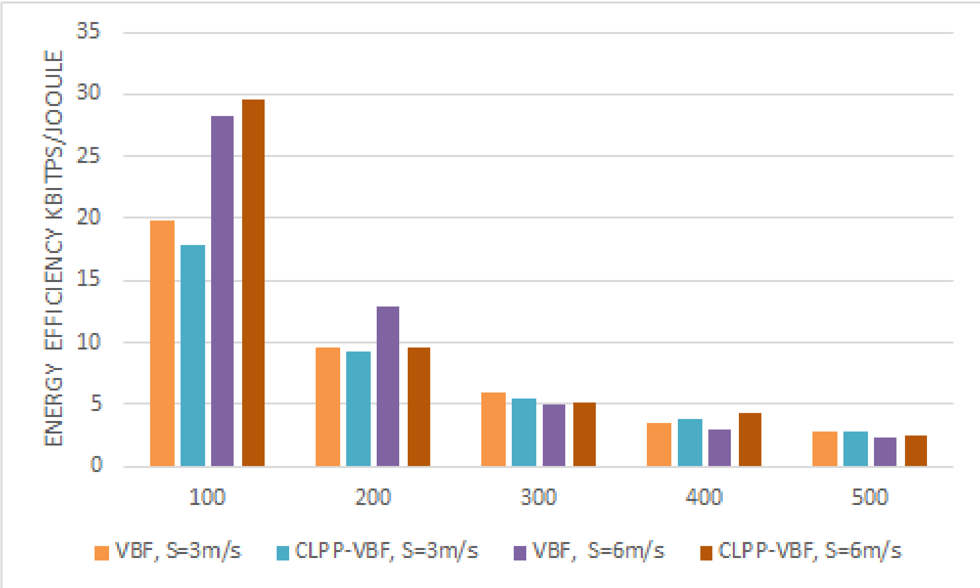

Figure 3.12 – *Energy Efficiency, W = 100m*

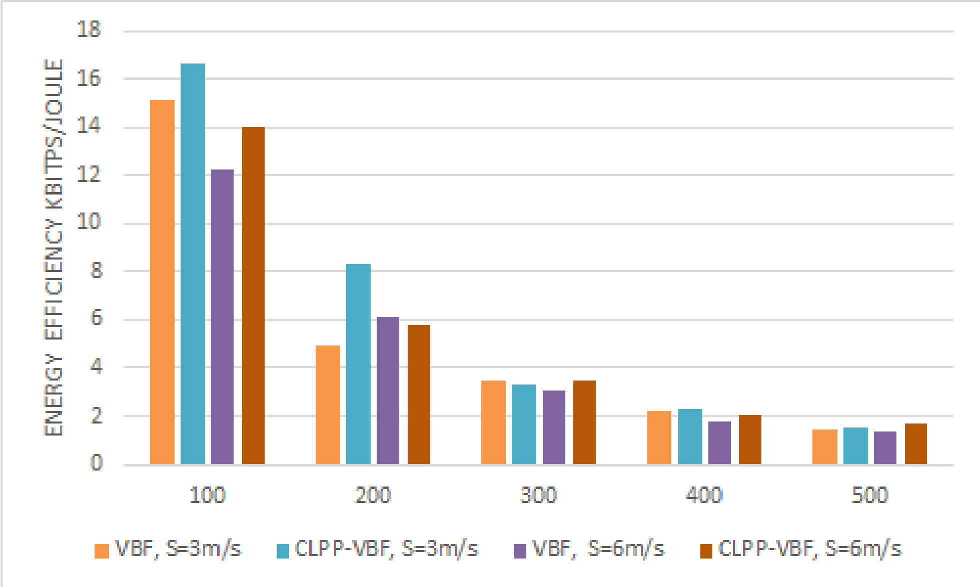

Figure 3.13 – *Energy Efficiency, W = 200m*

3.3.4 Performance comparison

The table 3.3 summarizes the obtained and highlights the gain that the proposed approach has achieved in different scenarios against VBF according to the cited metrics (PDR, AE2ED, EC, EE).

Radius = 100 m

- As it is illustrated on the table 3.3, the successful delivered data is more with the scenario at speed = 3 m/s than the scenario at speed = 6 m/s with 1.33 %, however, where the speed = 6m/s, we can observe that the average delay has been widely reduced, in addition, more energy has been saved, and the energy efficiency has been improved, hence the proposed approach has proven it efficiency against VBF and bring good performance results when the speed of sensors is more than 3 m/s for the reason that the proposed study indicates and prevent from wireless link that are prone to fail caused by the mobility of sensors, the method brings a mechanism that replace the sensor concerned with the link failure or breakage by selecting a new forwarder node, opposed to the VBF that does not consider the effectiveness of link before sending packet.

Radius = 200 m

- The results represented in the table 3.3 with radius W = 200 m, proves that CLPP-VBF brings better network performance than VBF where speed = 6m/s, since the proposed work achieves a large gain of the successful delivery data, energy saving and efficiency, with more reduced average delay than the results represented at speed = 3m/s with 0.27 %, we can conclude that CLPP-VBF performances in a dense network with a large speed level has been proved, as the proposed work adopts the method of new candidate forwarder node, and recover the packet loss, hence the successful data rate has been raised as the VBF does not re-transmit lost data. Where the node speed increase (6 m/s), the wireless link are more prone to fail, since sensors are frequently, otherwise when sensor speed decrease (3 m/s), the link failure are less prone to fail, for the reason that sensors are not moving with a large distance, hence CLPP-VBF proves it efficiency in a case where sensors are moving faster.

According to the table 3.3, The proposed CLPP-VBF has provided better results and improves the basic VBF protocol in a dense network at a large speed level.

Table 3.3 – *Performance results comparison for CLPP-VBF*

Radius W =100 m								
Metric	**Packet Delivery Ratio**		**Average End to End Delay**		**Energy Consumption**		**Energy Efficiency**	
Speed m/s	**3 m/s**	**6 m/s**	**3 m/s**	**6 m/s**	**3 m/s**	**6 m/s**	**3 m/s**	**6 m/s**
Gain %	6.98 %	5.65 %	5.52 %	14.41 %	3.03 %	25.39 %	1.2 %	4.12 %
Radius W =200 m								
Metric	**Packet Delivery Ratio**		**Average End to End Delay**		**Energy Consumption**		**Energy Efficiency**	
Speed m /s	**3 m/s**	**6 m/s**	**3 m/s**	**6 m/s**	**3 m/s**	**6 m/s**	**3 m/s**	**6 m/s**
Gain %	4.54 %	18.28 %	5.94 %	6.21 %	11.99 %	16.23 %	20.32 %	12.59 %

Conclusion

Among the numerous challenges that the UWSN technology are confronting, the issue of the link failure and interruption between sensor nodes within a given network has been provided and addressed in this chapter. We presented an overview about the main causes that conduct to a link deficiency during a wireless communication, the reasons can be multiple, as the frequent movement of the underwater sensors due to the water current or their mobility.

Our contribution has provided a new mechanism implemented in a cross-layer design that weakens the bounds between the layers and enhance the information sharing. The proposed method prevent from link deficiency and avoid unnecessary transmission.

In other part, the presented work was conducted to predict and prevent from link failure problem using the Lagrange Interpolation polynomial to evaluate the link efficiency at first. the forwarding selection process has been improved in such a way that the link reliability between sender and receiver node is taken into account before any forwarder selection, in addition we introduced a rediscovering phase that has allowed a sender node to find another available path, to gain more delivered packets and reduce the delay time.

The presented protocols have been based and implemented on the Vector Based Forwarding routing protocol (VBF). From the presented results it has been shown that the CLPP-VBF has provided good performance in term of delivery ratio, end-to-end delay, and the energy consumption at a highest speed level.

The following chapter provide another major issue in addition of the mobility of sensors, where the link quality is taken into consideration in the forwarder selection policy, the contribution is implemented using a different interpolation polynomial method.

CONTRIBUTION II: A Predictive Mechanism based on Newton interpolation

4

Contents

Introduction

The Underwater sensor network are composed of numerous devices that can be fixed and anchored at a certain position or can be mobile with the ability to move towards random regions, despite the several benefits and advantages that could those devices brings to the human and scientific community, the underwater sensor can faces numerous challenges, since they are equipped with a limited battery which is difficult to recharge or replace, a sensor can be easily exhausted while forwarding and transmitting packets frequently, and consumes it stored energy, hence, during a transmission a sensor with a low remaining energy can affect the received signal strength which make the delivered data packet unreliable, in other part, the presence of some interference and noises can harshly affect the communication between sensors within a network for the reasons that the received signal is attenuated through the present interference and noises.

Evaluating the link quality before any transmission that can be measure through multiple parameters is an important task for wireless sensors, since the communication link reliability plays a critical role for data transmission. Several factors can generates a deficiency link or a temporary loss of connectivity. In this work we have taken into consideration three major problems that can be the main causes of those problems cited above, the limited energy of sensors, noises and mobility of nodes.

- **Limited energy power :** despite the limitations of the underwater sensors is the energy constraints, where the underwater devices have a limited battery power that is not easily recharged or replace, which results in a low received signal and unsteady network topology.
- **Noises :** in the marine environment noises can be generated due to many different sources as the wind, shipping, thermal, and the turbulence, which induces in a poor received acoustic signal.
- **Node's movement and mobility :** underwater sensors can be fixed or freely mobile, their continuous movement affect significantly the routing performance, failures and interruption are generated.

This chapter provides a state of the art related to the main targeted problems, the proposed approach has been conducted to overcome the link and node failures problems with a prevention mechanism, the chapter include as well the simulation and performance evaluation of the implemented algorithm using the Vector-Based Forwarding protocol, the obtained results are discussed along with a performance comparison study.

4.1 State of the art

We present in the following part, some of the related work intended to evaluate the communication link efficiency between sensors within a network and addressed the problem of node failure due to a low remaining battery power, or even weak communication link.

- **The time-dependent link failure model :** since the wireless sensors equipment are confronting to several challenges the wireless links and sensors are prone to fail that might result a loss of the shortest path between a sensor node and it target node, [Zonouz et al., 2014] have introduced a time-dependent link failure model that includes the battery discharge model of sensor, it energy consumption, and the reliability of channel. As the offered energy of a battery and the value of it discharge capacity is depending on the battery characteristic and it condition loading, a technique that models a given discharge battery is required, for that a resultant functions is used to model a discharge curve of a battery power.

In addition the energy consumption of the sensor node is taken into account by the time-dependent model that is evaluated with a given formula that consists of 'sleep and active modes' (duty cycle) of a node and it battery discharge value, besides the channel conditions that is taken into consideration by the time-dependent model, it performance and quality are determined by the signal to interference and noise ratio (SINR) which determines a successful communication, the SINR has to be higher than a certain predefined threshold to ensure the reliability of the wireless communication, the SINR is computed according to the desired signal power, and the interference and noise power, thereafter, the total interference are computed based on a new proposed method by the authors which is 'A lognormal shadowing propagation model' that makes the path-loss model more accurate.

The total generated model can defines if a link between sensors may exist or those nodes can not directly communicate. The approach has been based on two routing algorithm to find the shortest path between sensor nodes and the sink node, the first routing algorithm use the Dijkstra method that is aimed to find the shortest path according to the reliability of the link, while the second algorithm makes use the breadth-first search (BFS) method that takes into account the minimum hop-count to find the shortest path. The approach of the time-dependent model has provided a better performance for it time delay and energy consumption reduction.

- **Backup Path with Energy Prediction based on Spanning Tree :** in this study, the network topology is organized as a spanning tree to facilitate the data aggregation technique, hence as the energy is severally consumed according to the Reconstruction of the spanning tree, [Lu et al., 2013] have proposed a mechanism that makes uses a back-up path that occurs when a sensor node is failed, in order to avoid unnecessary global Reconstruction of the tree, the mechanism includes a prediction method to estimate the possibility of node failure to overcome the problem of redundant path. During a data transmission packet, several nodes within the network are prone to fail, the communication between the alive nodes can be severally affected, for that the authors have provided a backup path mechanism to rebuild the failed path between the intermediate nodes and their descendant nodes to ensure the communication reliability.

  Thereafter the backup path requires a certain energy, so if there is several number of nodes that are building the back up path, a high overall energy consumption will take place, for that a method is included a dynamic prediction method in order to localize the sensor nodes with a high probability of failure. The predicted value of the energy consumption for data aggregation E_k^{ec} is computed based on the radio expands for transmitting m bits of data according to the distance d, and the radio expands for the receiving data as well, besides that a dynamic threshold E_k^{th} is computed according to the predicted value and an additional residual energy for the spanning tree control. Once the actual energy of the node is calculated by the predicted value it has to be compared with the predefined threshold, if $E_k^{ec} < E_k^{th}$ then the backup paths have to be built.

  The approach has provided the benefits to locate the nodes with less residual energy and avoid the build of the redundant paths, moreover the threshold has improved the method, for the reason that, when the network energy becomes it can adjust it value according to the current energy of the overall network.

- **Channel-Aware Routing Protocol (CARP) :** in [Basagni et al., 2015] proposed new distributed cross-layer routing protocol that takes into account the link quality and reliability information by considering residual energy, buffer space and the power control for the transmission of data, recent history of successful transmissions for the relay nodes selection, and the hop count information for avoiding void of shadow zone and routing around them. The protocol goes through two steps ,the first one is the network initialization and hop count settings where nodes have to know their hop distances from the sink by exchanging 'hello' packets.

The second step is the data forwarding, when a node x want to transmit a data it has first to send a control packet named PING in order to find the best relay node among it neighbors, upon receiving the PING packets, nodes will reply with a PONG packet to the sender, and then the node will select the best relay by checking the number of packets that thus nodes can get ,their residual energy, and either their link quality with the node x , all those information are carried in the PONG packet. The link quality of a sensor node is measured and estimated based on the success of transmission history with it reachable sensors, where the weight of recent transmission are more prominent than the past transmission.

Then a node x can start transmitting data as much as the selecting relay node can receives on it buffer. CARP has proven it efficiency in delivering packets with a reasonable time and low energy consumption for it robust relay selection mechanism.

- **A Fault Detection and Recovery Technique (FDRT) :** in this proposed approach the underwater network is organized as cluster, where each cluster has a specific sensor that is responsible for collecting data from the other member sensor of the cluster (CM), that is called cluster head (CH). The problem that arises with cluster is when the (CH) fails due to the battery power depletion or hardware errors that may affect and degrades the performance of the network, [Goyal et al., 2018] have proposed a novel technique that is aimed to select first a back up cluster head (BCH) beside the (CH) in a case that the CH can not operates any more, the BCH is elected according to it node density, the remaining energy, distance to the sink, and it link quality.

  The main purposes of the (FDRT) is to detect the CM and CH failure and provide a quick recovery, the failure are detected based on the low residual energy of the sensor or it hardware status, when a CH is detected as failed the BCH is immediately selected as the new CH, otherwise if the BCH is failed another sensor member of the cluster CM will be selected as the new CH, meanwhile every CM node sends a reply message to it according CH, if the reply message is not sending by a CM node within a certain period, the communication with the concerned CM is considered as failed, in this case the BCH is charged to collect data from the failed CM.

  The fault of the CM node can be caused due a node or communication failure problem, to distinguish between the two situations, (FDRT) provides a mechanism to evaluate the source of the fault, first if the reply message is not received by the CH within a given period the probability of the CM fault is due to communication failure, otherwise if the reply message is not received by the BCH within a certain time interval the probability of the CM fault is due to node failure. The (FDRT) has proven it robustness in term of successful delivery data with low energy consumption, beside a small end to end delay time.

- **Link Failure Detection Algorithm (LFDA) :** [Draz et al., 2019] have targeted the link failure that can be caused by the energy power breakage, the method has for purpose to detect accurately the location of the link failure or weaker link for a future link interruption, beside that a recovery mechanism is proposed by creating a virtual route to transfer the data packet. Assuming that the network is organized as cluster under two-dimensional deployment, where the network consist of sensors, actors and gateway, when a source node has data packet to transmit it first issues a Route Request message RREQ through the network, if any node does not reply with a Route Reply message RREP, then a message is sent to the gateway that will inform the nearest actor node that will look for the RREP which does not have been sent and detect then the link failure, this information alert is sent to the sink node inside the cluster that will use an alternative path until the breaking path will be recovered.

After that the link failure has been detected, the actor node will replace the previous node that has not reply to the RREQ message, issues a RREP to the corresponding RREQ using a virtual links, all link failures locations and the data of the corresponding nodes are stored. The recovery process is repeated until the virtual links are replace with the original links and the network became steady. The LFDA mechanism minimizes the future link failure and avoid the traffic overload caused by link deficiency.

Data packets are transmitted only if transferring time is less than a predefined threshold and it is depending also on the Euclidean distance between the nodes within the network, since the basic VBF does not take into consideration the link quality, there is no an accurate guarantee that data packets are all delivered, a directional flooding based routing protocol has been proposed, the technique use a packet flooding by nodes which are controlled, and the selected forwarder nodes decide to forward according to the quality of the link.

4.2 Proposed Approach for detection and prevention from weak link and failure problem

In this section, we illustrate our proposed approach, by giving an explanation about the problem discussed in this contribution, then the proposed solution aimed to avoid unreliable link quality is presented and described.

4.2.1 The Predictive Threshold Zone PZ_{TH}

Before that a node can be selected as forwarder, it predict signal value $P(t_{PT})$ has to be computed according to three input parameters. Those parameters have to be retrieved from data frames information (Receiving power signal strength RSS_i and their according Time T_i), and compared to RSS_{TH}. In order to reduce the computation process of $P(t_{PT})$ we defined an area within the transmission range of the sender node called predictive threshold zone PZ_{TH} as it is shown on Figure 4.1, the purpose is to ensure that only nodes located inside this area have to compute it predict signal value and compared to the RSS_{TH}, to make sure if a link interruption can occur or not, by measuring the link efficiency. The calculation of the PZ_{TH} is described as follow is same as previously described in Chapter 3., hence the allowed valid range for a node in the proposed method (CPN-VBF) is [0;DN_{TH}], where DN_{TH}=$Tr_{distance}$ − 2*PZ_{TH} , and it transmission range R_N is [0;R_N], where R_N= R-PZ_{TH}.

4.2.2 Problem description

As the UWSNs are widely deployed and the marine environment is considered as a large scheme [Zhou et al., 2009], many problems can be submerged, and due to the mobility of nodes, in a major time, a sensor node can easily moves and change it current position, that can affect the network topology, and became further compared to it sender's transmission range, while still remaining within the pipeline. Or moving away from the vector, where it projection to the vector became larger, generating a data packet loss, and a large delay time, at this time the sensor can creates void zone (a node with no path leading to destination), and affect the network performances, meanwhile it could simply regain it older position by returning inside it sender's range.

Although, as the underwater wireless sensor are equipped with limited battery power [Sahana et al., 2018] that can be low to forward data constantly, the received signal became too weak, the link quality between sender and receiver is not fairly good to receives a complete data packet, a node cannot be elected as the next forwarder if one of those criterion cited above are not verified. Since the basic VBF does not takes into account the link reliability before any forwarder selection, our proposed method is aimed to review the issues explained above before any forwarder selection based on a prediction model during the transmission cycle of any node. With the given Figure 4.1 below, where S is the original sender, F is the forwarder, and A the receiver node considering the following problem statements :

- The node A can drift away the range of the forwarder F while still located inside the routing pipeline, the received signal strength becomes weak, for the reason that the acoustic signal is attenuated which may results in a loss of data packet. Meanwhile the node A can join the range of the forwarder F as the sensor nodes are considered as mobile nodes.
- The node B is located inside the allowed range of the forwarder F, but in the meantime the received signal strength can be affected as well and poorly received, due to the presence of some marine interference or the low remaining energy of the node B.

As the basic routing protocol VBF does not takes into consideration the efficiency of the communication link between sensors before transmitting that can be affect by several reasons, we have proposed a new method that is aimed to evaluate the efficiency of the link quality before sending data and prevent from future link breakage or failure and isolate the considered sensor until it became qualified and suitable to receive and transmit, we have defined a predictive threshold zone PZ_{TH} where each sensors that moves inside the regions have to be evaluated to determine if it has the probability to leave the range or not. Considering two sensor nodes F and A, where S is the original sender, F is the forwarder, and A the receiver node

- $d(A,S)$ The distance between A and S computed using the Euclidean distance described in the Equation (3.4)
- $Tr_{distance}$ Transmission distance for VBF
- R the transmission range for VBF
- DN_{TH} Transmission distance for the proposed method (CPN-VBF).
- R_N The transmission range for the proposed method (CPN-VBF).
- PZ_{TH} The predictive Threshold Zone
- $\overrightarrow{TS}$ The vector of the routing pipeline
- P The projection of node to the vector $\overrightarrow{TS}$ computed using the Equation (3.2) and Equation (3.3)
- RSS_A The received acoustic signals strength at node A according to *d(A,S)* calculated as :
- RSS_{TH} The received acoustic signal strength threshold (the required amount of signal to receive a data packet), according to PZ_{TH}, where $l = d(F,x)$ calculated with the Equation (3.1).

- $P_{(tPT)}$ The predicted acoustic signal strength value according to $RSS_{A(i)}$ calculated with Newton Interpolation polynomial at t_{PT}
- t_{PT} The predict time.

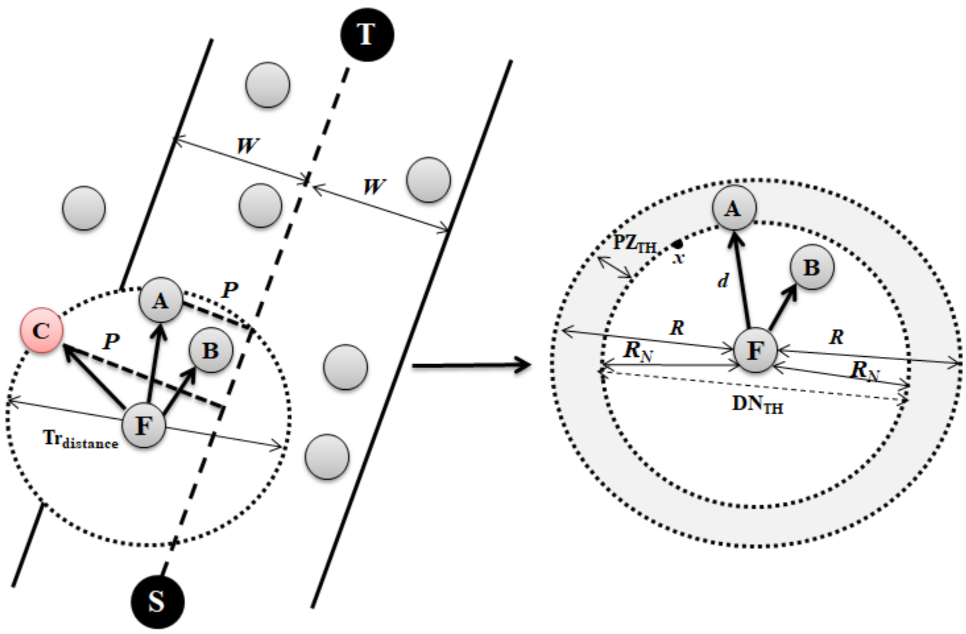

Figure 4.1 – *Problem description*

From the Figure 4.1, the link reliability between node F and A is measured according to the prediction model used to predict the received signal strength at t_{PT} time, the purpose is to evaluate the link in such a way that if $P_{(tPT)}$ is less than the predefined signal threshold RSS_{TH} , the probability that the node A can moves out the range is ensures, otherwise the node is not moving outside the range it could regain a near location from the sender. In other case, the received signal strength at node B (RSS_B) is similarly compared with the predefined signal threshold RSS_{TH} , if it is less than RSS_{TH} , it means that the node B has a low remaining energy level that makes the received signal strength too weak to receive a successful data packet. Our proposed predictive cross-layer mechanism to detect a weak link and prevent from unnecessary forwarder selection issue is described.

4.2.3 Proposed solution

Our approach cooperates between the medium access layer MAC and the network layer in a cross-layer mechanism. The determination and the prediction of a broken link are processed at the MAC-layer using the received power signal strength. By applying the newton interpolation polynomial a link can be evaluated if it can be failed or not. Before that a node can be selected as the forwarder at the network layer, it has to ensure if it is concerned by the link failure or not, for that we used a variable named "xmit reason" with the value "XMIT REASON HIGH RSS" to indicate that the concerned node is reachable, otherwise the variable will take the value "XMIT REASON LOW RSS" to indicate a link with low efficiency, depending on the xmit reason variable the node will decide whether it can be elected as forwarder for this transmission or not. The notations used in the proposed approach are described in the following table :

1. First of all, considering that the node A is receiving a data frame it has to determine first if it belongs to the routing pipeline, for that, it will computes it orthogonal projection

Table 4.1 – *Notation used in the proposed algorithm*

Notation	Meaning
Pkt	Packet
$Trans_{time}$	Transmission time, where i ∈ [1;3]
T_i	Receive time, where i ∈ [1;3]
RSS_i	Receive signal, where i ∈ [1;3]
Node_ID	ID of the concerned node
Sender_ID	ID of the sender node
NI	Newton Interpolation polynomial
A_{ID}	ID of the node A
F_{ID}	ID of the node F
SRC_ID	ID of the source node
FD_ID	ID of the forwarder node
$T_{adaptation}$	The delay time of the Self-adaptation algorithm

distance with the vector (TS), where T is the target and S is the original source. By given the coordinates of A(x_A, y_A, z_A), T(x_T, y_T, z_T), S(x_S, y_S, z_S),and $\overrightarrow{TA}$ the vector formed by the target and the node A. The projection P_{TA} to vector $\overrightarrow{TS}$ is computed using the Equation (3.2) and Equation (3.3). After the projection of A, the coordinates of A' are as follow : A'($x_{A'}, y_{A'}, z_{A'}$), notice that A' belongs to $\overrightarrow{TS}$, the distance d(A,A') is then defined with the Euclidean distance (see the Equation (3.4)) The distance d(A,$\overrightarrow{TS}$) is compared with the using radius 'W' value of the pipeline if $d \leq W$, the node belongs to the routing pipeline, then it distance with the source node d(A,F) is calculated using the Euclidean distance (see the Equation (3.4)), then it is compared with DN_{TH}, if d(A,F) is high than DN_{TH} and less than the transmission distance range as follow : $DN_{TH} \leq d(A,F) \leq$Tr$_{distance}$, then the node A is within the Prediction Zone (i.e A ∈PZ$_{TH}$) a probability of a future link failure is expected.

Otherwise if d(A,F) is less than DN_{TH} : d(A,F) ≤DN$_{TH}$, the node A is inside the allowed transmission range. In other cases, if the sensor node is inside the allowed range of its forwarder then if it received signal strength is lower than the the received threshold signal as : $RSS_B \leq RSS_{TH}$, the received signal is too weak according to the low residual energy or the presence of interference that weakens the received signal, which may results in a link failure, otherwise it can simply continue it forwarding process.

2. When the node A is located at the PZ_{TH}, at this time we can expect a probability of a link interrupt between A and F, or it could regain the range field and become closer to the source, to light up those both situations, three consecutive received data frame information (Received Power Signal Strength RSS and their according received Time) from the same source F to the node A are retrieved, for that, at first the source node F or a forwarder broadcasts a data frame to it one next hop neighbors inside it range, when a node A receives the frame it will computes it projection with the vector and distance with the sender F, described previously.

   If its distance with F indicates that it is located at the prediction zone, it predict signal value for a future estimation has to be computed, for that as it was cited previously, VBF has limited 2 received packets per a second, so if the number of data frame received by node A from sender S is 2, the first and the second received signal strength by the node A are collected according to their respective times, in this case the sender S will reset it transmission status and resend again a copy of the last data frame after a certain time computed with the Equation (3.5) to avoid any collision problem. The data frame is now received by node A the third received signal strength according to it time is collected. In other case, if the received data frame from S to A was limited at 1, the sender S will reset it transmission status and resend two copy of the last data frame after a certain time of period defined by the Equation (3.6) and Equation (3.7).

Since VBF has limited two received packets per a second, hence the approach creates a third copy of the last frame and resend it to the concerned destination, in order to gather three consecutive information packets, within a certain time interval $T[t_1; t_3]$, the RSS_i and their received Times T_i are retrieved where I $\in$ [1;3]. The additives packets will be obviously dropped once the RSS and the time T are retains, to avoid any collisions problems. The time of the received data Frame is calculated with the Equation (3.8), where $Transtime_i$ is the transmission time, and v_0 is the propagation sound speed in the water.

Newton Interpolation Polynomial : the Interpolation polynomial gives an estimation according to 'n' input parameters at x value, the general equation is given by :

$$P_n(x) = \sum_{k=1}^{n} f[x_0...x_k] \prod_{k-1}^{i=1} (x - x_i) \tag{4.1}$$

In out study, the purpose is to obtain an estimation value of the received signal at t time according to three received signal strength with to their respective times, to acquire a certain accuracy about the predict signal value for a future estimation. $P_{(tPT)}$ is calculated as :

$$P(t_{pt}) = f[x_1] + f[t_1, t_2](t_{pt} - t_1) + f[t_1 t_2 t_3](t_{pt} - t_1)(t_{pt} - t_2) \tag{4.2}$$

Where t_{PT} is the predict time and (t_1, t_2, t_3) are the respective times of the received packets, and

$$f[t_1, t_2, t_3] = \frac{f[t_2 t_3] - f[t_1 t_2]}{t_3 t_1}$$

$$f[t_1, t_2] = \frac{f[t_2] - f[t_1]}{t_2 t_1}$$

$$f[t_1] = P_1, f[t_2] = P_2, f[t_3] = P_3$$

Where P_1, P_2, P_3 are the respective received signal. the predict time is defined as :

the predict time is defined as :

$$t = t_3 + M_t \tag{4.3}$$

Where Mt is the average value of the measurement [Boukli-Hacene et al., 2014].

$$M_t = t_3 - \frac{t_1 + t_2 + t_3}{3} \tag{4.4}$$

Once the interpolate signal value of the signal strength $P_{(tPT)}$ is calculated using the Newton Interpolation polynomial, it is compared with $RSS_{(TH)}$ The predefined signal strength threshold defined by the Equation (3.1) If ($P_{(tPT)} < RSS_{(TH)}$) and the first received signal strength is high than the second, and the second is high than the third as follow ($RSS_{(1)} > RSS_{(2)}$ and $RSS_{(2)} > RSS_{(3)}$), it indicates that the node A is moving out the scope and the received signal by A is too weak to be attempt, there is a high possibility of a link failure. By the use of the "xmit reason" variable to prevent the network layer about the link efficiency, this variable will take a value of "XMIT REASON LOW RSS", in a case where the received signal is low, indicating the "Node ID" concerned and it "sender ID" to the upper layer.

Otherwise "xmit reason" will take a value of "XMIT REASON HIGH RSS", which means that the receiving signal is good enough and the node A can continue it forwarding process and no link failure is taking place. In other way, when a node B is inside the allowed transmission range ($d(B,F) < DN_{(TH)}$), if it received signal strength compared with the $RSS_{(TH)}$ is too weak ($RSS_{(B)} < RSS_{(TH)}$), the "xmit reason" will indicates a LOW RSS, in addition the "Node ID" concerned and the "Sender ID".

3. In VBF, a node is selected as forwarder according to it projection value that should be less than RADIUS 'W', in our approach, we brought a new method for the forwarding selection policy, a node has to check if it is eligible to be the forwarder by computing the it projection to the vector and and it "xmit reason" value. If the signal is low (i.e. "xmit reason" == "XMIT REASON LOW RSS"), the node check if it is the concerned node, according to the previous sending node with the value indicated by "Node ID", if so, the node will simply discard the data packet, and not be selected as forwarder and has to be isolated for the fact that : since the UWSN are 3 Dimensional patterns a node can moves away from it sender's range toward the sink while still remaining inside the pipe, this fact will affect the received signal that have an impact on the delivered packet, in other way the node can get far from in sender's and the vector of the pipeline as well, this will affect the received signal and the delay time, for the reason that a large projection distance increases the desirableness value. Otherwise if the signal is good enough (i.e. "xmit reason" == "XMIT REASON HIGH RSS") , the node will continue it forwarding process and can be elected as the forwarder.

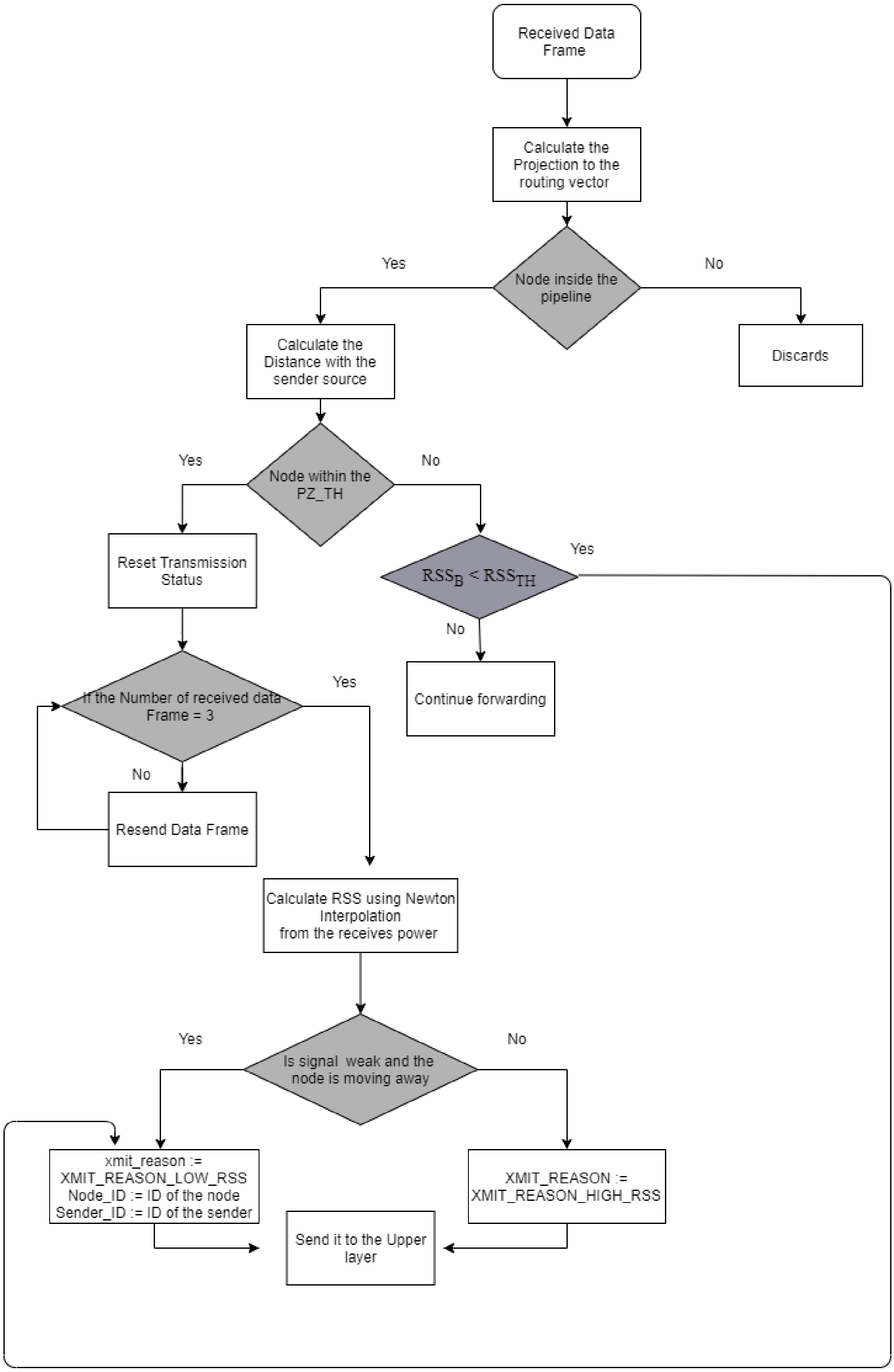

Figure 4.2 – *Process of the proposed mechanism*

Algorithm 4 Pseudocode of the proposed mechanism

```
Step 1 : Node A receives Pkt_i from F ;
Step 2 : Calculate Projection(A);
Step 3 : Get the coordinate (x, y, z)_{A'} after Projection(A);
Step 4 : Calculate d(A,A');
if d(A, A') ≤ W  then
  Calculate d(A, F)
  if D_{TH} ≤ d(A, F)&d(A, F) ≤ Tr_{distance}  then
    Get(Trans_{time(1)}, RSS_1);
    i := number_received_pkt;
    while i ≤ 3 do
      ResetTransStatus(F);
      Get (RSS_i);
      Calculate the receiving time T_i;
    end while
    Get (RSS_i);
    Calculate NI (T_i, RSS_i)
    if NI ≤ RSS_{TH}&RSS_1 > RSS_2&RSS_2 > RSS_3 then
      xmit_reason := XMIT_REASON_LOW_RSS
      Node_ID := A_{ID}
      Sender_ID := F_{ID}
    else
      xmit_reason := XMIT_REASON_HIGH_RSS
    end if
  end if
  if  d(A, F) < D_{TH} then
    if RSS_A < RSS_{TH} then
      xmit_reason := XMIT_REASON_LOW_RSS
      Node_ID := A_{ID}
      Sender_ID := F_{ID}
    end if
  end if
end if
Step 5 : Get DATA Pkt
Step 6 : Check if A is close to the Routing Vector
if Close(A) then
  if xmit_reason = XMIT_REASON_LOW_RSS  then
    if Node_ID = A_{ID} & Source_ID = SRC_ID or Source_ID = FD_ID  then
      Free Pkt
    end if
  else
    Calculate Desirableness(A)
    Calculate Delay T_{adaptation}
    Forward Pkt
  end if
end if
```

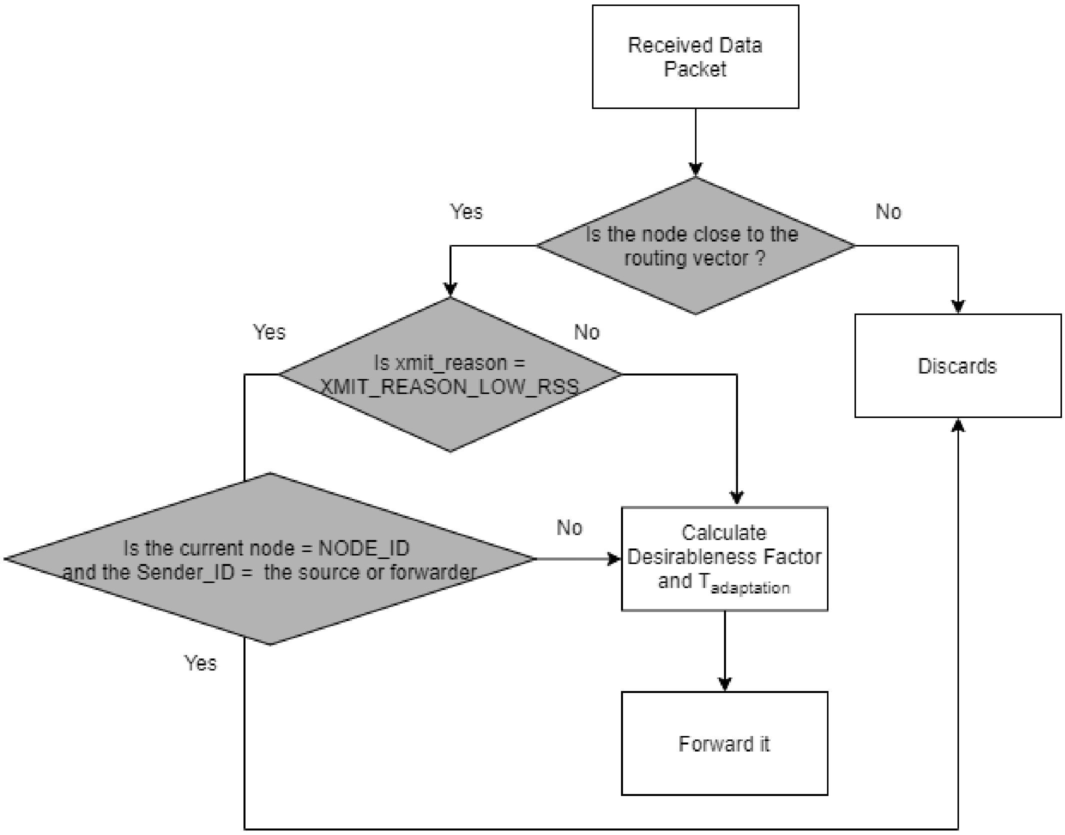

Figure 4.3 – *Process of the proposed mechanism*

4.3 Simulation and performance evaluation

In the previous section, some of the studies related to the link and node failure have been cited and explained, in this section, our two proposed approaches intended for the detection and prevention from future link or node failures are presented and illustrated firstly, the main goals of this study is to improve the operation of the VBF routing protocol by exploring the weaknesses that the protocol can have, we added a defined predictive zone to evaluate the link efficiency between two sensor nodes, once the node is located at this area, and by using the two well-known interpolation polynomial Lagrange and Newton in our two respectively proposed approach, a future link interruption with a sensor node can be detected and prevented in a cross-layer manner.

Thereafter the obtained results are discussed and explained, depicting our simulation environment used to evaluate and elaborate our results we used the open source Network Simulator 2 (NS-2) with an extension Aqua-Sim that support the acoustic signal communications in UWSN and three-dimensional network deployment, providing a set of basic protocols [Xie et al., 2009].

4.3.1 Simulation environment

The used simulation environment is represented in the following table 4.2 : We use a three-dimensional space (1000 m x 1000 m x 1000 m), the Source S and the target T are fixed at (1000,0,0) (0,1000,1000) respectively, the nodes are randomly deployed, the Radius of the pipeline is varied W = [100,200,300] meters, The Range is fixed at 100 meters, we varied number of nodes from (100 to 500), the speed of node is varying between 2m/s, 4m/s, 6m/s, their initial energy Eo is 10000 joule, the packet size is set at 50 Bytes ,the number of received packets is 2 per second, the transmission of the acoustic signal power is set at 0.2818 Hertz, the frequency is 25 Khz the simulation time is 200 seconds, the MAC layer bit rate is set at 10 Kbps.

Table 4.2 – *Simulation parameter used for CPN-VBF*

Simulation Parameter	Value for CLPP-VBF
Deployment area	(1000 m x 1000 m x 1000 m)
Network topology	Random grid
Number of nodes	(100,200,300,400,500)
Routing protocol	VBF, CPN-VBF
Radius	100 m , 200 m, 300 m
Range	100 m
Node speed	2 m/s, 4 m/s, 6 m/s
Initial energy	10000 j
Packet size	50 Bytes
Number of packet	2 Packet / sec
Frequency	25 Khz
MAC protocol	UnderwaterMAC
MAC layer bit rate	10 Kbps
Communication medium	Acoustic waves
Speed of sound	1500 m /s

4.3.2 Performance metrics

We evaluate the performance of our proposed approach (CPN-VBF) against the basic VBF using the following metrics: The Packet Delivery Ratio, Average End to End Delay, Energy Consumption and Energy Efficiency.

1. **The Packet Delivery Ratio (PDR) :** is a metric that gives the ratio of the number of the delivered data packets at sink node, according to the number of the sending data packets by the source :
$$PDR = \frac{\sum Received_{Packets}}{\sum Sending_{Packets}} \times 100 \quad (4.5)$$
2. **The Average End to End Delay (AE2ED) :** represents the average time needed to ensure the data packets reach the destination (Sink).
$$AE2ED = \frac{\sum R_{time(i)} - \sum T_{time(i)}}{\sum Received_{Packets}} \quad (4.6)$$
Where $T_{time(i)}$ is transmission time of the packets, and $R_{time(i)}$ is the received time.
3. **The Energy Consumption (EC) :** illustrates the total difference between the initial energy E_0 and the residual energy E_r of sensor nodes
$$EC = \sum(E_0 - E_r) \quad (4.7)$$
4. **The Energy Efficiency (EE) :** which is successful delivery of data at the sink node with the amount of energy consumed in the network [Ketshabetswe et al., 2019]:
$$EE = \frac{successrate \times totalpacketsenttothesink}{totalenergyconsumed} \quad (4.8)$$

4.3.3 Result discussion

In this section we explains the simulation performance according to the metrics explained previously, we varied the speed of the node, and the radius of the routing pipeline at each simulation, to clarify their impact on the network performances.

1. **The impact of the node speed :** As the node's mobility can have an effect on the network performances, we varied the speed at different level (2m/s, 4m/s, 6m/s), for both VBF and CPN-VBF, the radius of the pipeline is fixed at W=100m.

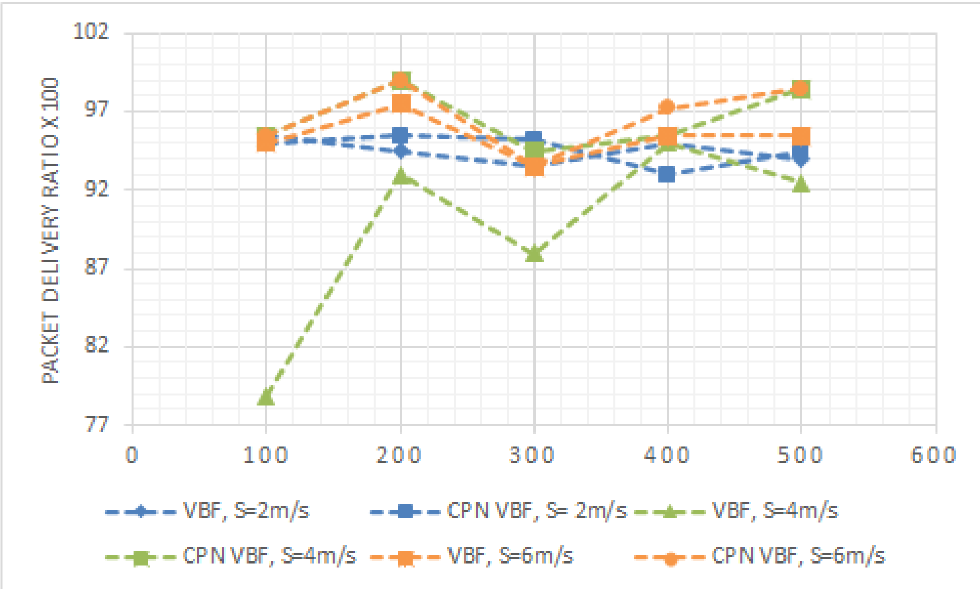

Figure 4.4 – *Packet Delivery Ratio with speed s=2m/s, s=4m/s, s=6m/s*

From the above figure, we can observe the delivery ratio at different nodes number, as much as the network is dense, the possibility to have a high number of nodes involved for the forwarding process increases, this can rise the number of received packet at the sink, although in some cases, even if the network contains a high number of nodes, there could be less nodes inside the pipeline, due to the node's mobility in a major time, that leads to few creating path within the pipeline, and a low delivered packet at the sink. According to the results presented in Figure 4.4, we can see the impact of the speed on the delivery ratio.

At speed = 2m/s, for both scheme, the speed had a light effect, the number of nodes present inside the pipe have a small speed level, hence their probability to move outside is low. At speed = 4m/s, we can observe for both scheme at scenarios '100', and '300' the reduction of the delivery ratio, in this case the speed level had an impact on the involved nodes inside pipe, in such a way that their probability to move outside was high, leading to many void zones created through the pipe, in other way at speed =6m/s, as we can see on both scenarios '100', and '300', for the two protocols, the received packet rate has decreased for same reason explained at speed = 4m/s, though, the PDR has raised for other scenario despite the speed level, for the reason that, as the UWSN are a 3D patterns, the nodes can moves towards the sink while still remaining within the pipeline.

As it is shown, our proposed protocol has provided better PDR against VBF, the mechanism that allows to verify the link quality between sender and receiver node that can be affect by the mobility of node in a major time, or energy level depletion, before any forwarder selection policy, has improved the protocol performances.

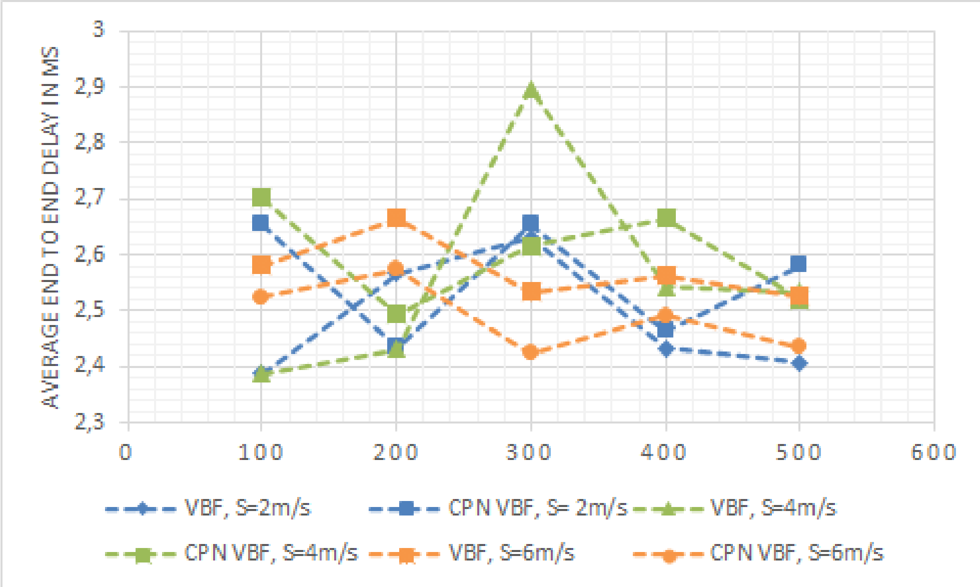

Figure 4.5 – *Average End to End Delay with speed s=2m/s, s=4m/s, s=6m/s*

The Figure above, shows the AE2ED at different nodes number, as we know previously, the basic VBF adjust the forwarding policy, with the self-adaptation algorithm, the node with a less desirableness factor has a small time to wait until it forward the data, and as much as the factor of the desirableness increases , the time to wait became larger, Generating a large overall end to end delay. The reason that leads the value of the desirableness raises, is the large projection of the node to the vector, or it large distance from the sender.

In other way, the presence of a large number inside the pipeline and near the vector, leads to decrease the delay time, but due to the effect of the mobility that can in some cases brings the nodes close to the vector, that reduce the delay time, otherwise it can takes the nodes away the vector that raises the delay time. At speed = 2m/s, even if the PDR, in Figure 4.4, has not been affected by the low speed level, the AE2ED has, for the reason that, the projection of nodes involved during the transmission process might be large, or it distance from the sender is large as well, which leads to a highest $T_{adaptation}$ value. For speed = 4m/s, we can observe a large delay at scenario '300', for the VBF scheme, following the results presented in Figure 4.5, where the PDR of VBF was reduced, it can explains the large delay, the node involved at the forwarding process became further than the vector due to the mobility, that generates a raise of AE2ED and a low PDR.

Despite the scenario '100' where both PDR and the AE2ED of VBF was low, this return to the fact the forwarders number was low within the pipe and close to vector at same time. We conclude that the AE2ED has no direct proportional relation with PDR in every scenario, it depends on node's position inside the pipe according to the vector and the sender node, as well their density. For speed = 6m/s, the delay time of CPN-VBF is reduced according to VBF throughout the simulation, the fact that takes into account the link reliability between sender and receiver that can be failed or interrupt due to the high mobility of nodes before that a forwarder can relay, and it isolation process to avoid a large delay, has provided an enhancement in term of AE2ED.

From Figure 4.6, As the Figure shows, the consumed energy throughout the simulation, generally depends on the number of nodes involved during the transmission process, the relation is proportional. As the radius of the pipeline is fixed at 100m/s, the speed level had a light effect on the consumed energy, the selected forwarders along the pipe are

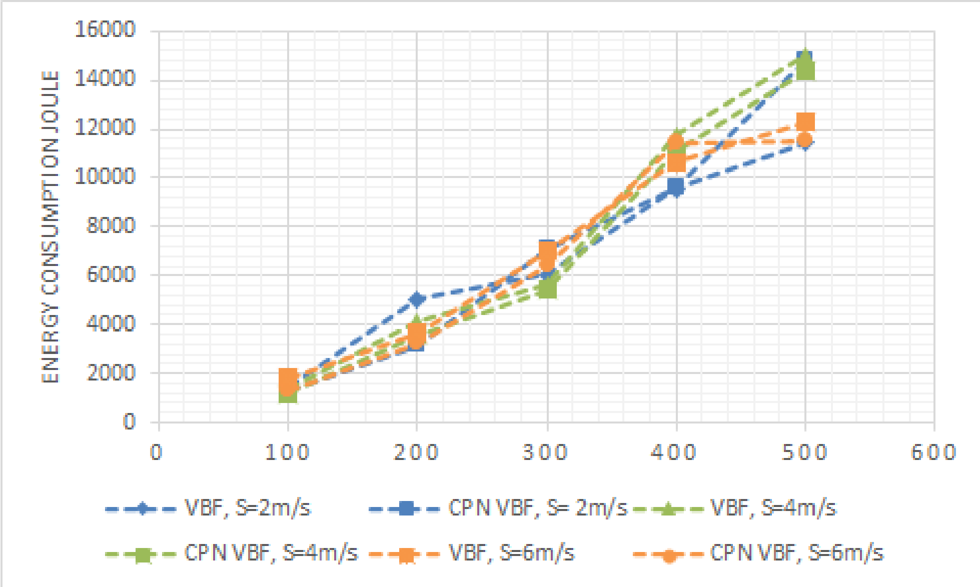

Figure 4.6 – *Energy Consumption with speed s=2m/s, s=4m/s, s=6m/s*

restricted. The mobility of node can decreases the energy consumption in such a way that the nodes can move out the pipeline and became no longer involved, otherwise, it can increases it, while the mobility of nodes can include large number of nodes within the pipeline.

CPN-VBF has the ability to overcome those nodes with low energy remaining, while they are located inside their sender's range, that has reduced the consumed energy at different speed level overall, meanwhile, the fact that CPN-VBF performs better that VBF at a high speed level, for it purpose to consider the link reliability between a sender and receivers that can be affected by the node's mobility, a low speed level can makes the CPN-VBF performs as the basic VBF, since there is a small probability of node's that can leaves their sender's range or pipeline as well.

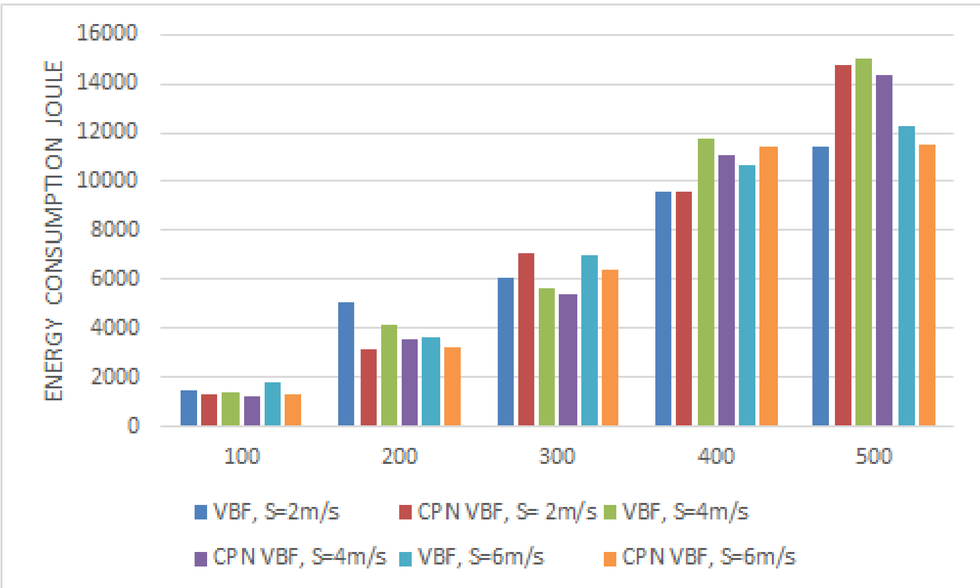

Figure 4.7 – *Energy Consumption with speed s=2m/s, s=4m/s, s=6m/s*

The Figure 4.7. Illustrates the energy consumption of the results presented in Figure 4.6, as we can see, CPN-VBF has reduced the consumed energy at speed = 4m/s for the fact that it mechanism avoids nodes with a weak link efficiency to be elected as forwarders, due to their mobility. We conclude that CPN-VBF outperforms VBF in term of energy consumption at a high mobility rate.

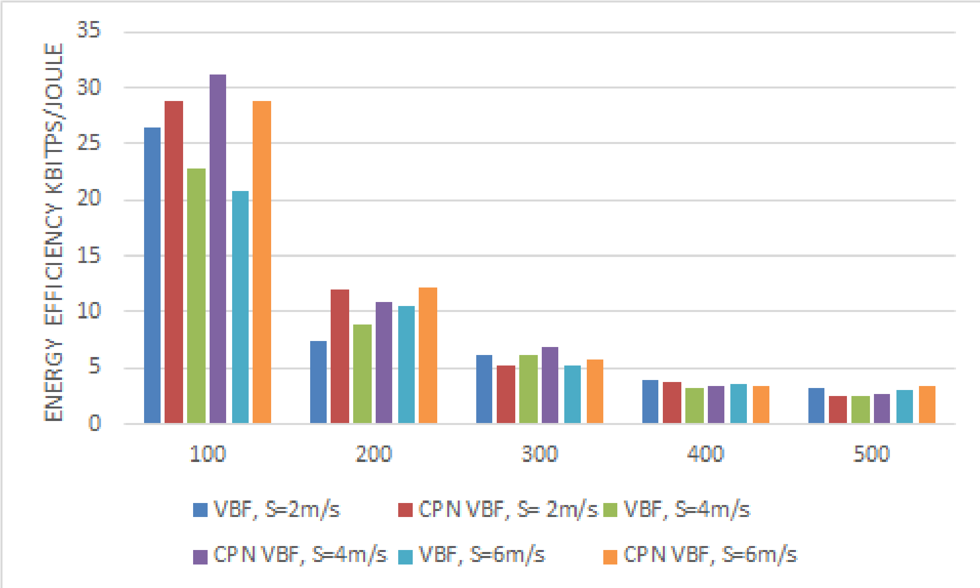

Figure 4.8 – *Energy Efficiency with speed s=2m/s, s=4m/s, s=6m/s*

The results presented in the Figure 4.8, demonstrates the energy efficiency according to the number of nodes with different speed level, as it is shown the energy efficiency is depending on the successful delivered data and the energy consumed as well, where the network is dense a large energy amount is consumed according to the figures (Figure 4.4, Figure 4.6, and Figure 4.7), the presence of numerous sensor nodes inside the pipeline may involves many forwarders and data packet transmission which may increases the consumed energy, hence a large PDR with a low energy consumed provides a high energy efficiency, otherwise a large PDR with a high energy consumed results in a low energy efficiency. CPN-VBF brings better performance in term of energy efficiency against the basic VBF, the mobility of sensor nodes provides additional forwarders inside the pipeline which may results in a good success rate, in this fact the energy consumed is depending on the network density and forwarder nodes, since the proposed mechanism avoid the transmission of data packet through an ineffective link more energy is saved.

2. **The impact of the pipeline radius :** in order to clarify the impact of the radius W the pipeline on the network performances, we varied the radius at different value (100 m, 200m, 300m), for both VBF and CPN-VBF, the node's speed is fixed at speed = 3m/s.

   As it is shown on the Figure 4.9, below, the PDR depends on nodes number present within the pipeline. As we can see when radius = 100m, the PDR increases all over the simulation results for both scheme (CPN-VBF and VBF), except for our proposed approach at scenario '200', where the PDR has been decreased, for the reason that nodes inside the pipe might be reduced due to their mobility, the presence of void zone (nodes with no path leading to destination) can affect the received data, even if our approach avoids a bad link quality and isolate the concerned node, in some scenario the lack of nodes present on some transmission range of a sender node, does not allow the selection of other available forwarders this can reduce the PDR.

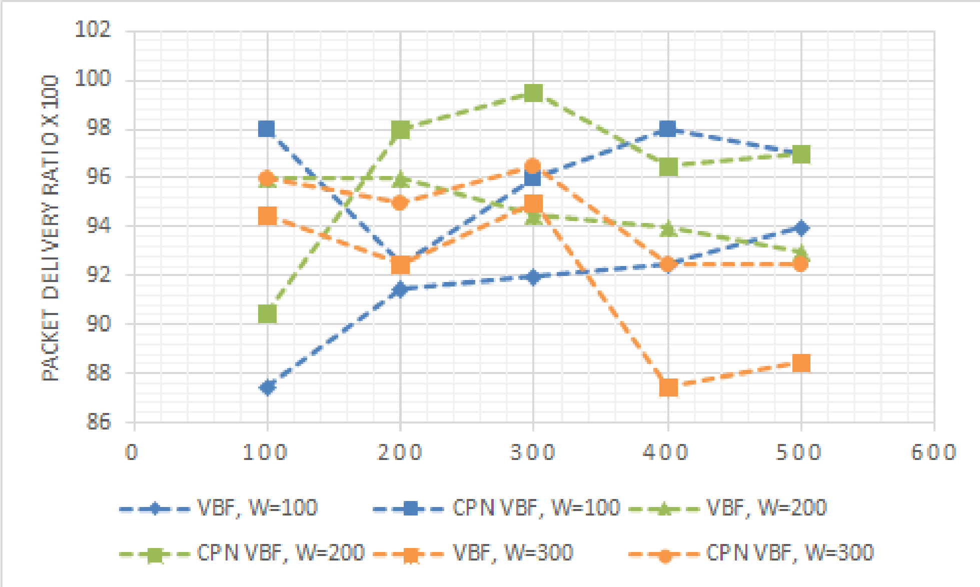

Figure 4.9 – *Packet Delivery Ratio with radius W=100m, W=200m, W=300m*

For radius = 200m and 300 m we can see that performance of the basic VBF has decreases, due to the network overload and queues saturation prompted by the high number of involved nodes inside the pipe, this might reduce the received data packets, we conclude that the performance of VBF diminish in a large deployed network.

CPN-VBF proves it performance in a dense network for the fact that received signal strength determines if a node can be elected as forwarder and pursue the transmission process, or it has to give the priority to another available node.

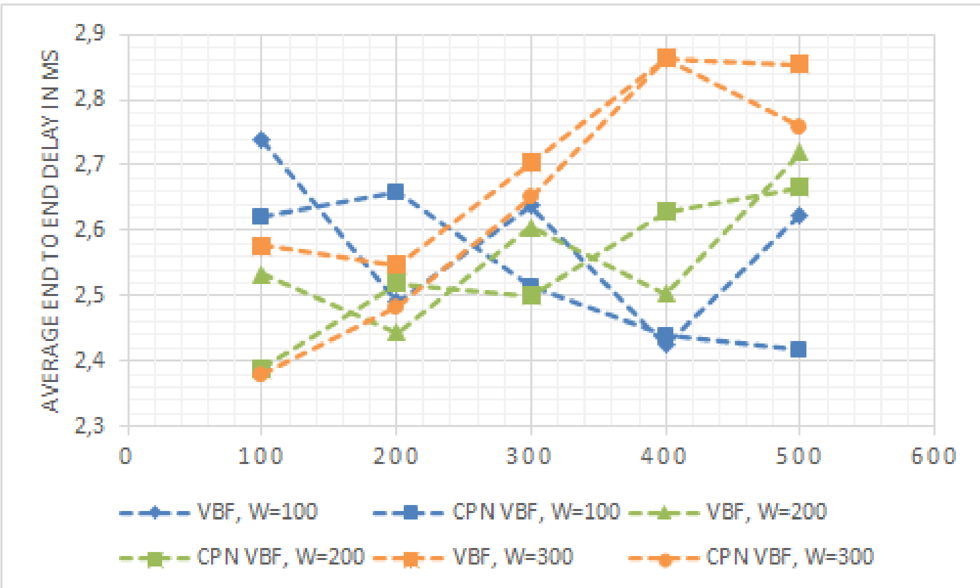

Figure 4.10 – *Average End to End Delay with radius W=100m, W=200m, W=300m*

The Figure 4.10, shows the impact of the radius on the AE2ED, as we already know, the delay is impacted by the data's forwarder position, it projection value from the vector, and it distance from the sender as well, that could makes the delay increases. As much as the radius is large the delay raise, this returns to the fact, nodes far from vector remaining inside the pipe can have a large projection distance, this raised the overall delay, in other case even if a node is near the vector it transmission range could contains a lack of nodes with no path that leads to the sink, this can increases more the delay.

For the results with radius =100m we can observe that the delay decreases as much as the nodes number increases, the presence of several forwarders inside the pipeline can makes the delay decreases, otherwise, at radius = 200 and radius 300 we notice that the delay time has increased as much as the number of nodes is, for the reason that when the pipeline became larger, nodes with a large projection distance will be involved too, that leads to a rise of the delay time. Our proposed protocol has reduced the AE2ED in a major time, for scenario with radius =300, CPN-VBF proves it well performance against VBF.

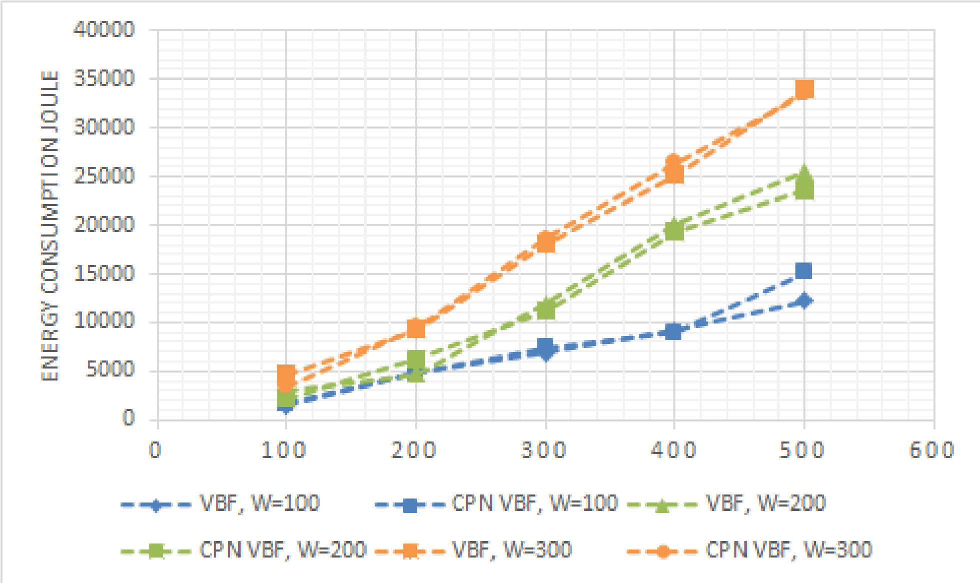

Figure 4.11 – *Energy Consumption with radius W=100m, W=200m, W=300m*

The below figures demonstrates the impact of the radius on the energy consumed, although the presence of many nodes inside the pipe leads to a high energy consumption, and as much as the radius became large the overall consumed energy through the networks increases as well, several nodes could participates at the forwarding process.

The Figure 4.12, illustrates the presented results at Figure 4.11, and gives a better demonstrations, as we can compared the two protocols in term of energy consumption. CPN-VBF consumes more energy than VBF in some cases, for the reason that, when the link between two nodes is predicted to be failed, the isolation process will allow to give the possibility to another available forwarder that satisfy the conditions that CPN-VBF has provided, this will involve another node to transmit and consume energy. Otherwise CPN-VBF consumes less energy than VBF in some scenarios, for the fact that the energy level of node before any election is taken into consideration, that will preserves the node from forwarding and reduces the consumed energy.

The Figure 4.13 above demonstrates the energy efficiency of both routing protocols with different pipeline radius, according to the figures (Figure 4.9, Figure 4.11, and Figure 4.12), the successful data rate is decreasing where the radius pipeline is large for the reasons that a large radius with a low speed can affect the network performance in such a way that the presence of many forwarders inside the pipeline that are slightly moving may increases the energy consumed and affect the delivered data. We can conclude that

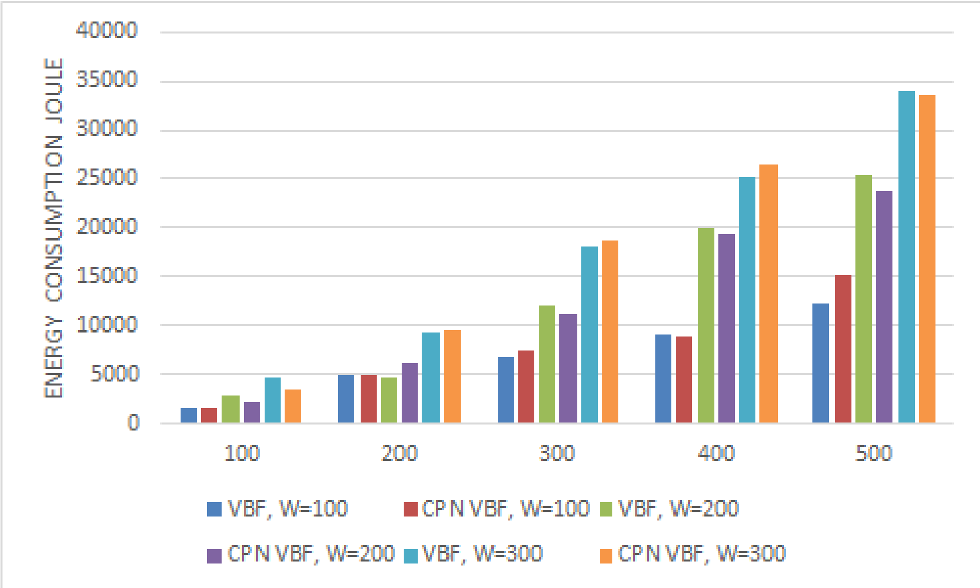

Figure 4.12 – *Energy Consumption with radius W=100m, W=200m, W=300m*

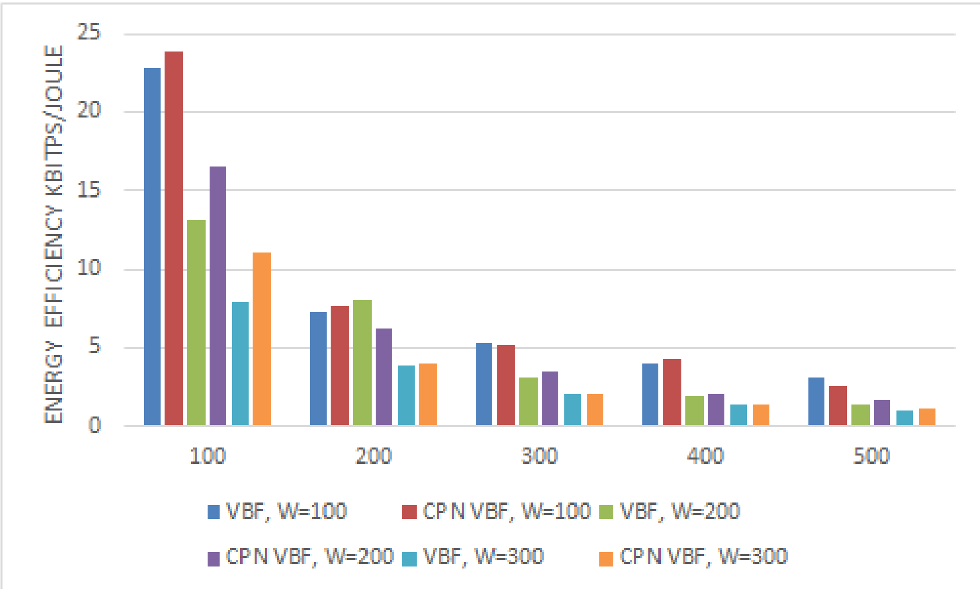

Figure 4.13 – *Energy Efficiency with radius W= 100 m, W=200 m, W=300 m*

the success rate was medium at first with a less forwarder nodes that gives a good energy efficiency, then the PDR has raised with a large number of forwarders leading to a high energy consumed that has decreased the energy efficiency, however, the presence of a large number of sensors inside the pipeline has reduced the successful data rate and increased the consumed energy which may results in a low energy efficiency. Eventually, the proposed mechanism has provides a good energy efficiency with a pipeline radius = 200 m.

4.3.4 Performance comparison

The table 4.2 summarizes the simulation results that represents the performance of the proposed routing protocol CPN-VBF against VBF according to the discussed metrics (PDR, AE2ED, EC, EE) , the represented results shows the gain that the proposed mechanism has achieved in different scenarios from the basic VBF.

The impact of the speed

- As it is illustrated, the results that represents the successful delivery packet are not performing with the scenario of speed = 2 m/s, however the average delay gained is medium and the saving energy is high, due to the low delivered data, hence the energy efficiency is low, the proposed mechanism does not provide a good performance with a low speed level.
- CPN-VBF has achieved better results with a scenario of speed = 4m/s in term of successful delivery data and the average delay time as well, with a high energy consumed, in other hand the energy efficiency is high, it means that even if the protocol has consumed more energy, the delivered packet achieved is large, thus we notice a decrease of the average delay, hence the proposed protocol has proven it efficiency with a speed = 4 m/s, for the reason that it mechanism prevent from sensor nodes with a poor link quality which may results in a data packet loss.
- The results that represents the scenario with speed = 6 m/s, shows the acquired delivery data is quite medium as same as the energy saving, however the results of the reduced delay indicates a low efficiency, whereas the energy efficiency is better high than the other scenarios, the results proves that CPN-VBF did not consume a large amount of energy for the reasons that, there was a low to medium delivery data, for the fact that the speed can affect the routing performance in such a way that nodes inside the pipelines may easily leave the pipe, which may results in a lack of sensor nodes inside the pipe, void zones can be formed and a high data packet loss is generated.

The impact of the radius

- The acquired delivery data with radius pipeline = 100 m is large, hence the reduced delay is medium to large, however the saving energy is low and the energy efficiency is poor, for the reasons that more there is data packet delivered more the energy is consumed, the proposed mechanism does not bring good results in term of energy, the speed level is set at 3 m/s, and the pipeline may contains a lack of sensor nodes, due to low radius value, hence the mobility is quite poor, the possibility for that a sensor node leave the range of it sender is low.
- The results that represent the scenario with radius pipeline = 200 m, demonstrates a low to medium gained data packet thus the energy saving, with a medium gained of energy efficiency and a reduced delay, even if the network is fairly dense, a large radius pipeline does not necessarily means that the pipe contains enough sensors to forward data, in other hand the mobility is low according to the pipeline, the possibility that a node could easily regain the pipeline may be reduced.
- The routing performance has provided a quite good results with a dense network (radius pipeline = 300 m), the gained data packet and the consumed energy are medium, besides a large reduces of the average delay and a high energy efficiency acquired, the proposed mechanism has proven it effectiveness in a dense network, for the reasons that it avoidance and prevention from sensor nodes with a poor link quality that could generates packet loss has improved the delay time.

We conclude that represented results in table 4.2, proves that the proposed mechanism has provides better results compared with the VBF protocol and performs well at a medium speed level = 4 m/s according to low network density, in addition CPN-VBF has provided good performance in a dense and large network deployment, with a speed = 3 m/s. The mobility of sensors can harshly affect the network performance in such a way that multiple sensors may drift away from the vector, hence a lack of sensor nodes may be involved in the forwarding process. During a transmission of packet from a forwarder to a node, the mechanism proposed evaluate the link efficiency, however, in mean time sensor nodes that are not considered by the transmission can leave the pipeline which results in a network performance depletion.

Table 4.3 – *Performance results comparison for CPN-VBF*

Metric	**Packet Delivery Ratio**			**Average End to End Delay**		
Speed m/s W = 100 m	**2 m/s**	**4 m/s**	**6 m/s**	**2 m/s**	**4 m/s**	**6 m/s**
Gain %	1.84%	16.75%	3.05%	4.98%	9.71%	4.17%
Radius m Speed = 3 m/s	**100 m**	**200 m**	**300 m**	**100 m**	**200 m**	**300 m**
Gain	10.77%	5.06%	5.21%	7.56%	5.33%	8.33%
Metric	**Energy Consumption**			**Energy Efficiency**		
Speed m/s W = 100 m	**2 m/s**	**4 m/s**	**6 m/s**	**2 m/s**	**4 m/s**	**6 m/s**
Gain %	12.77%	4.47%	6.22%	15.94%	26.93%	27.84%
Radius m Speed = 3 m/s	**100 m**	**200 m**	**300 m**	**100 m**	**200 m**	**300 m**
Gain %	0.85%	7.11%	3.88%	3.89%	20.77%	28.86%

Conclusion

Link failures and temporary loss of connectivity occurs frequently due to the poor link quality because of the mobility of nodes, their low remaining energy, the acoustic signal attenuation and absorption. In this contribution we have proposed a new predictive routing protocol using the Newton Interpolation polynomial in order to evaluate the link reliability, and distinguish from two situations : the first, when the link can be interrupted or failed following the mobility of nodes, that could moves far from their sender and pipeline as well, second when a node is moving away from it sender node and could probably returns to it old or last position within the range, in other case despite the existence of the node inside the allowed transmission range, it low residual energy affect the received signal strength, and it is also considered as a future link interruption as well.

Our method was implemented in a cross-layer manner, that performs with combination of the Medium Access Control (MAC) layer and the Network layer, for the earlier detection and prediction from link failures and breakage problems, the forwarder selection takes into account the link quality during it transmission cycle before any data forwarding. CPN-VBF has proven it efficiency and robustness in link failures prevention and has improved the VBF protocol performance in term of packet delivery ratio, average delay, and energy saving.

The following chapter initiate a comparison study of the implemented mechanism against the poor acoustic link quality and their failures, where the radius pipeline and node's speed are varied, the obtained simulation results are evaluated according to different metrics, discussed and summarized.

Performance Comparison 5

Contents

Introduction

Nowadays the Underwater wireless sensors are becoming very widely use [Ahmed et al., 2017] for the numerous benefits and advantages that it can bring to the scientific researchers and human beings as well, however the underwater sensors are confronted to several challenges, as their limited bandwidth and battery power, their low propagation delay, the cost of their deployment and maintenance, their localization challenges, ambient noises and interference [Awan et al., 2019, Fattah et al., 2020]. The design of robust and efficient routing protocols is the main purpose for the researchers, hence multiple approaches have been proposed and evaluated to overcome certain issues and fails.

As the underwater sensors are characterized by a limited battery, the frequent data sensing, receiving and sending consumes a significant energy, in other hand, the presence of interference inside the marine environment and noises caused by shipping, water salinity, temperature and other [Awan et al., 2019] affect the routing performances, in addition since certain underwater devices are mobile, they have the ability to continuously moving towards different region, hence the received signal strength is severally affected.

Multiple studies have been conducted to predict poor acoustic link quality and provide mechanisms to recover from it [Khasawneh et al., 2020], in this thesis, the main objectives and purposes was to bring new methods to enhance the routing performances with the failures prediction, our contributions are based on Polynomial Interpolation, an effective manner to estimate the efficiency of the acoustic link and include it in the Vector Based Forwarding protocol, the proposed methods were described and detailed, the obtained results were discussed and illustrated previously, in this chapter we presents a performance comparison of the proposed contributions over the basic VBF to evaluate more the effectiveness of both protocols, and to demonstrates which mechanism is the best to adopts. The evaluated contributions are the following :

- A Cross-Layer Predictive and Preemptive Routing Protocol for UWSN using the Lagrange Interpolation (CLPP-VBF).
- A Predictive Mechanism based on Newton interpolation (CPN-VBF).

The experimentation of the routing protocol performances in a real environmental conditions is essential, however the deployment of underwater sensors, their maintenance, in a large environment is costly, hence in order to analyze the routing performances, the simulation is significant to model and understand the overall network performance under different conditions, moreover the simulation bring the advantage to determine the parameters that have the greatest impact on routing performance as well [Nayak et Vathasavai, 2016, AOUIZ, 2020].

This chapter introduce a simulation and performance comparison of the implemented mechanism over the VBF, the simulation environment and parameters used to analyze the protocols are explained, along with the performance metrics utilized to discuss the results, the obtained results are described and explained as well with a summarizing tables that depict the gained percentage for each proposed technique.

5.1 Simulation and performance comparison

5.1.1 Simulation environment

In order to evaluate the proposed approaches (CLPP-VBF and CPN-VBF), we have used the following simulation parameters represented in the table 5.1, three-dimensional space (1000 mx 1000 m x1000 m) is used, the Source S and the target T are fixed at (1000,0,0) (0,1000,1000) respectively, the nodes are randomly dispersed, the Radius of the pipeline is varied W = 100,200, The Range = 100 meters, we varied number of nodes from (100 to 500) , the maximum speed of node is varied S= 3m/s,6m/s their initial energy E_0 is 10000 j, the packet size is 50 Bytes, the number of received packets is 2 per second, (depending on the VBF protocol), the transmission of the acoustic signal power is set at 0.2818 Hertz, the frequency is 25 Khz the simulation time is 200 seconds, the MAC layer bit rate is set at 10 Kbps.

Table 5.1 – *Simulation parameter used for the comparison performance*

Simulation Parameter	Value
Deployment area	(1000 m x 1000 m x 1000 m)
Network topology	Random grid
Number of nodes	(100,200,300,400,500)
Routing protocol	VBF, CLPP-VBF, CPN-VBF
Radius	100 m , 200 m
Range	100 m
Node speed	3 m/s, 6 m/s
Initial energy	10000 j
Packet size	50 Bytes
Number of packet	2 Packet / sec
Frequency	25 Khz
MAC protocol	UnderwaterMAC
MAC layer bit rate	10 Kbps
Communication medium	Acoustic waves
Speed of sound	1500 m /s

5.1.2 Performance metrics

The performance of the proposed approaches (CLPP-VBF and CPN-VBF) have been evaluated using the following metrics The Packet Delivery Ratio (PDR), Average End to End Delay (AE2ED), Energy Consumption (EC), and Energy Efficiency (EE) described as follow :

1. **The Packet Delivery Ratio (PDR) :** represents the success rate, the number of data packet delivered to the sink node, according to the number of sending packets by the source :

$$PDR = \frac{\sum Received_{Packets}}{\sum Sending_{Packets}} \times 100 \tag{5.1}$$

2. **The Average End to End Delay (AE2ED) :** represents the average time needed for a data packet to achieve the destination (Sink).

$$AE2ED = \frac{\sum R_{time(i)} - \sum T_{time(i)}}{\sum Received_{Packets}} \tag{5.2}$$

   Where $T_{time(i)}$ is transmission time of the packets, and $R_{time(i)}$ is the received time.

3. **The Energy Consumption (EC) :** represents the total difference between the initial energy E_0 and the residual or remaining energy E_r of the sensor nodes

$$EC = \sum(E_0 - E_r) \tag{5.3}$$

4. **The Energy Efficiency (EE) :** the metric represents the successful delivery of data at the sink node over the amount of energy consumed in the network [Ketshabetswe et al., 2019]:

$$EE = \frac{successrate \times totalpacketsenttothesink}{totalenergyconsumed} \tag{5.4}$$

5.1.3 Result discussion

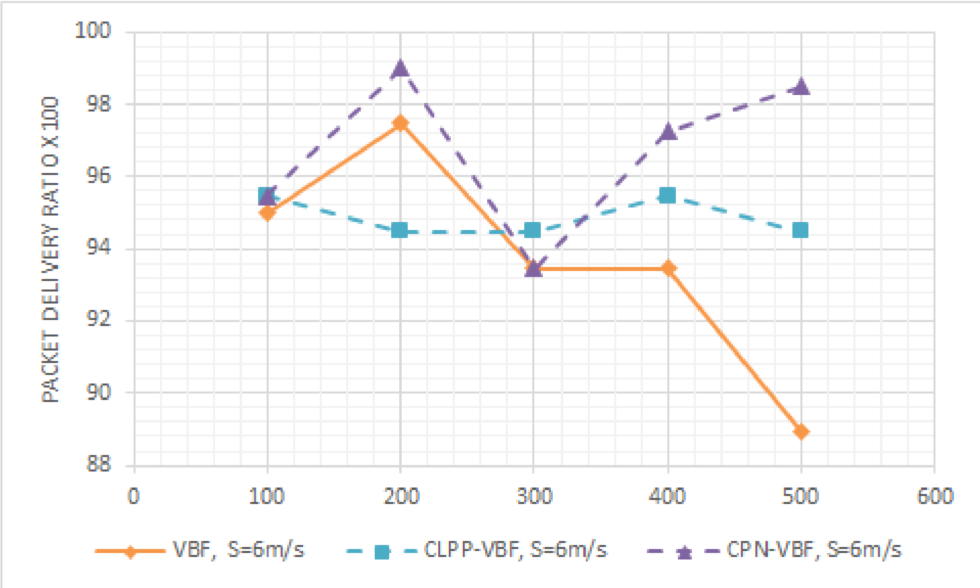

Figure 5.1 – *Packet Delivery Ratio W =100 m, s= 6m/s*

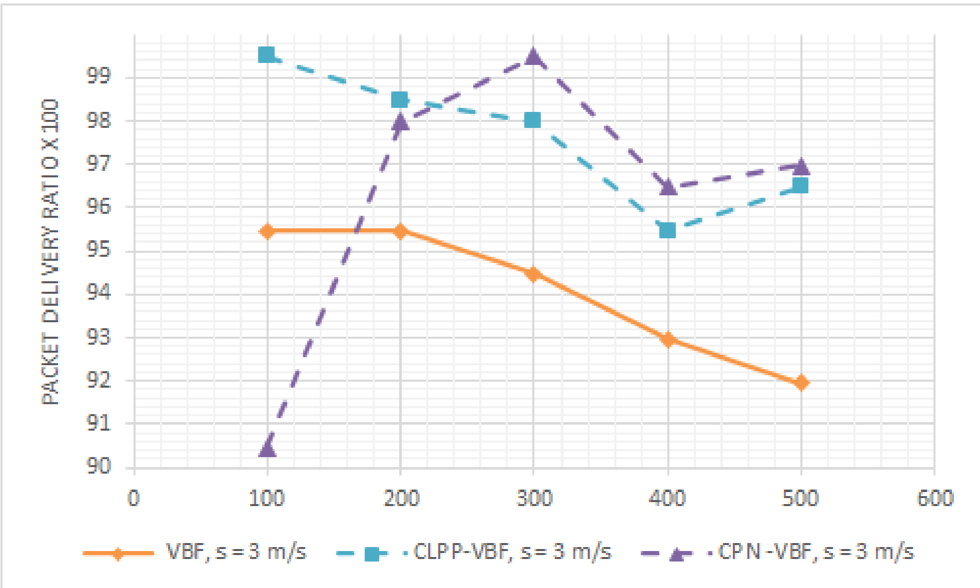

Figure 5.2 – *Packet Delivery Ratio W =200 m, s= 3m/s*

The figures 5.1 and 5.2 demonstrates the Packet Delivery Ratio of the proposed approaches (CLPP-VBF and CPN-VBF) against the VBF protocol according to nodes number, the Figure 5.1 illustrates the obtained results with a radius W = 100 and speed = 6 m/s, it is obvious that the speed has an impact on the network performances, since the mobility may severally affect the routing, where nodes are continuously moving, the link interruptions are more prone to occur, which results in a low successful delivery data. The performance of the VBF protocol are decreasing according to the Figure 5.1 as the protocol is not quite efficient with a speed = 6 m/s, as the nodes are moving faster, the routing pipeline may contains a lack of sensors and void regions, in the meantime more sensor nodes could move inside the pipeline and became forwarders, the proposed approaches have provide better results than VBF, for the prediction of failure mechanisms, CPN-VBF has achieved better results than the CLPP-VBF in the term of delivery data, according to the Figure 5.1.

As it is shown on the Figure 5.2, in accordance with the obtained results, the VBF protocol is less efficient with a radius pipeline W = 200, than CLPP-VBF and CPN-VBF, the presence of a large number of sensors inside the pipeline may generates sensors overloading and duplicate packet, that can significantly reduce the delivered packet and consume more energy, hence CPN-VBF adopts a mechanism that is able to define poor acoustic link due to low residual energy which is caused by the continuous data forwarding of node.

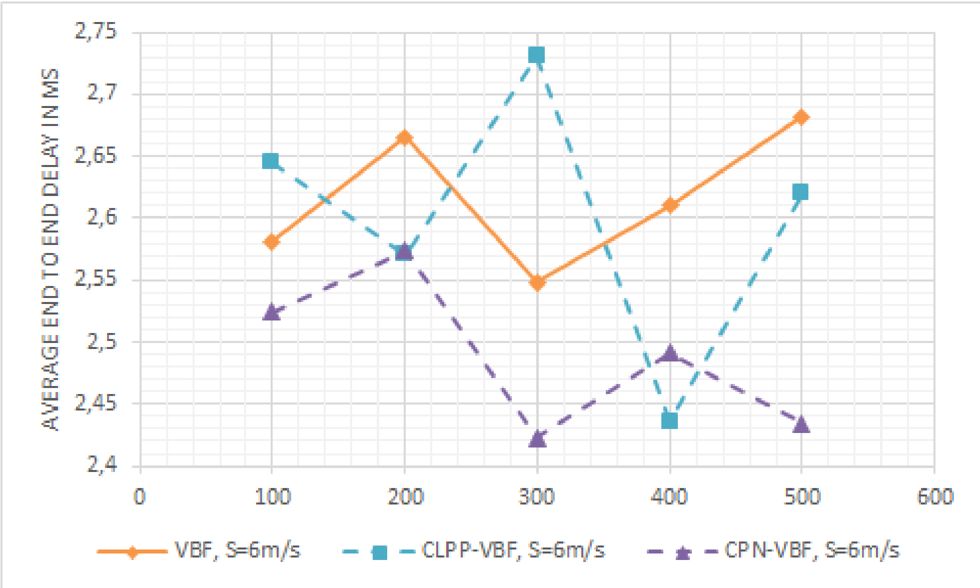

Figure 5.3 – *Average End to End Delay W =100 m, s= 6m/s*

From the Figure 5.3 and 5.4, the represented results shows the impact of the Average End to End Delay over the number of nodes for all protocols, the results obtained with in both figures proves that the CPN-VBF has provided better performance in term of delay time, it is obvious that the average end to end delay is affected by the number of sensors within the network, since the presence of numerous nodes increase the delay time, in other hand, the nodes that are overloaded increase and affect the delay time as well, the presence of lack of sensors inside the range of the pipeline due to the mobility of sensors of link failures induces a large delay that explains the results represented in the Figure 5.3.

Moreover the sensor nodes that are inside the pipeline and far from the vector provoke a large delay since that the protocol VBF adopts the Self-adaptation algorithm that delay the data packet according to the $T_{adaptation}$, a large projection value induce a large time to wait. CLPP-VBF is less efficient than the CPN-VBF for the reason that the protocol recover the lost data packet with a new forwarder selection from the sender node, this mechanism may provoke the node overloading.

The consumed energy is represented in the figures 5.5 and 5.6 for the results obtained with a radius = 100 m and speed = 6 m/s, where the results shows that the proposed CPN-VBF has a low energy consumption than VBF, since the proposed mechanism avoid unnecessary trans-

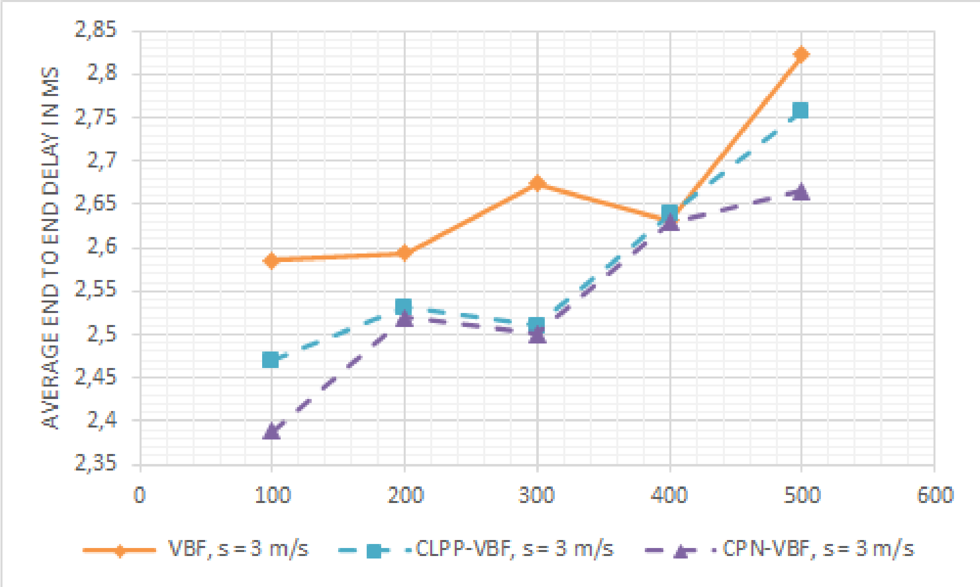

Figure 5.4 – *Average End to End Delay W =200 m, s= 3m/s*

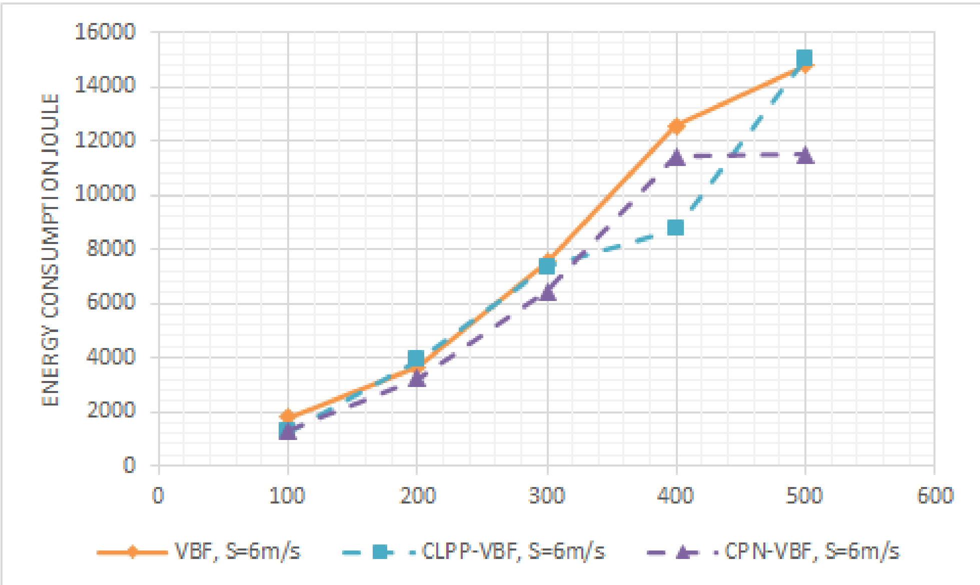

Figure 5.5 – *Energy Consumption W =100 m, s= 6m/s*

mission and prevent from future poor link that can provides failures, which saves more energy, however, CLPP-VBF consumes more energy than CPN-VBF and VBF in some scenarios for the reason that the proposed approach may includes more forwarder in a case where a link failure may occur due to the mobility of sensors, and according the speed = 6 m/s, sensors are more prone to drift away from their sender, CLPP-VBF consider it as future failures, the protocol adopts a mechanism that include and involve more forwarder where the sender range contains no available sensors to replace the concerned node, this induces more energy consumption in some time.

The results represented in Figure 5.7 and 5.8 demonstrates the consumed energy over the number of nodes, where the achievement are better and more efficient for both (CLPP-VBF and CPN-VBF) compared to VBF, the presence of failures is low when the devices are less faster (speed = 3 m/s), this induce a low energy consumption by CLPP-VBF that provide a

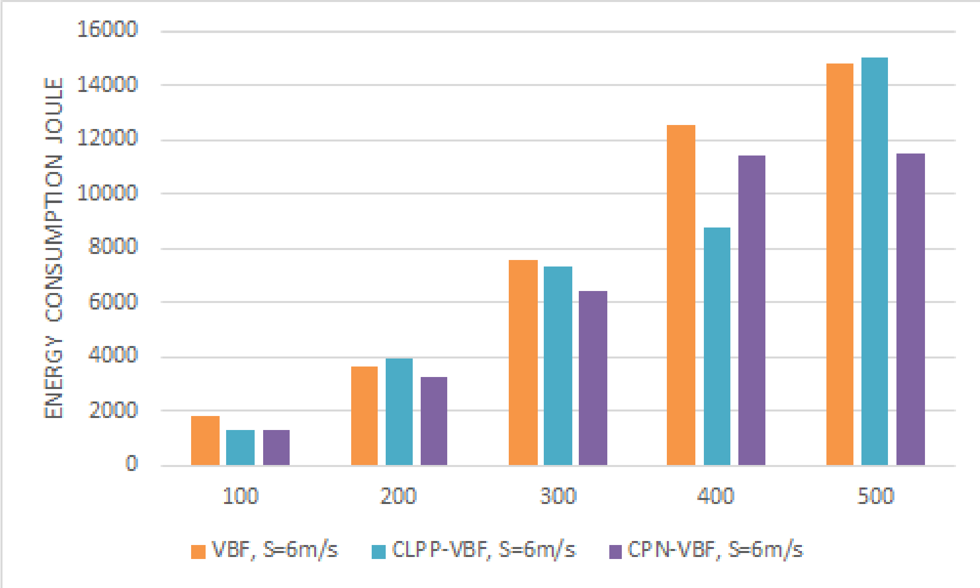

Figure 5.6 – *Energy Consumption W =100 m, s= 6m/s*

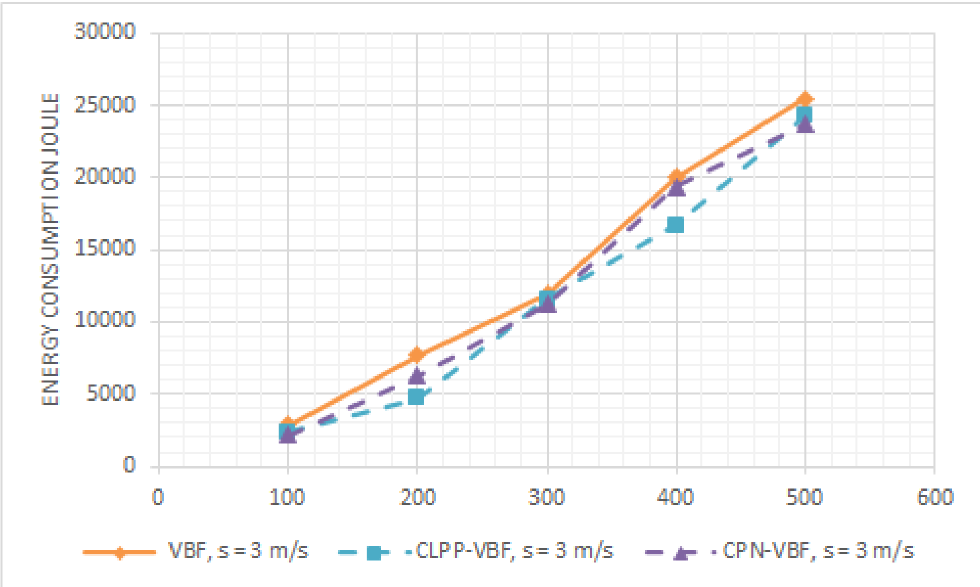

Figure 5.7 – *Energy Consumption W =200 m, s= 3m/s*

mechanism which prevent from failures due to the mobility of sensors, though the CPN-VBF may consume more energy compared with CLPP-VBF in a large pipeline radius, for the reason that the proposed protocol detect poor and inefficient acoustic link due to several reasons as low remaining energy, presence of interference and noises which affect the received signal strength, and according to a large pipeline that involved many forwarder nodes, several packet and duplicate packet are continuously forwarder, that can consumed more energy and generates the overloading and lead to a poor received signal strength, CPN-VBF takes into consideration inefficient acoustic link and prevent from weak link, and as the pipeline contains a large number of nodes, the method generates additive frames to obtain more information for the prediction concept, that induce more consumed energy.

The Energy Efficiency metric is represented in the figures 5.9 and more illustrated in the Figure 5.10, CPN-VBF has proven it efficiency compared with VBF and CLPP-VBF, although,

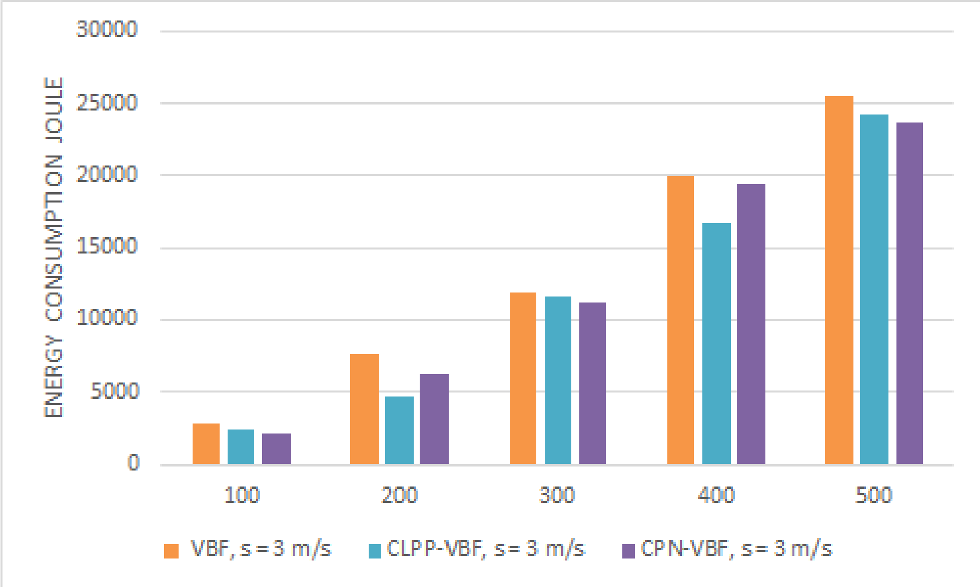

Figure 5.8 – *Energy Consumption W =200 m, s= 3m/s*

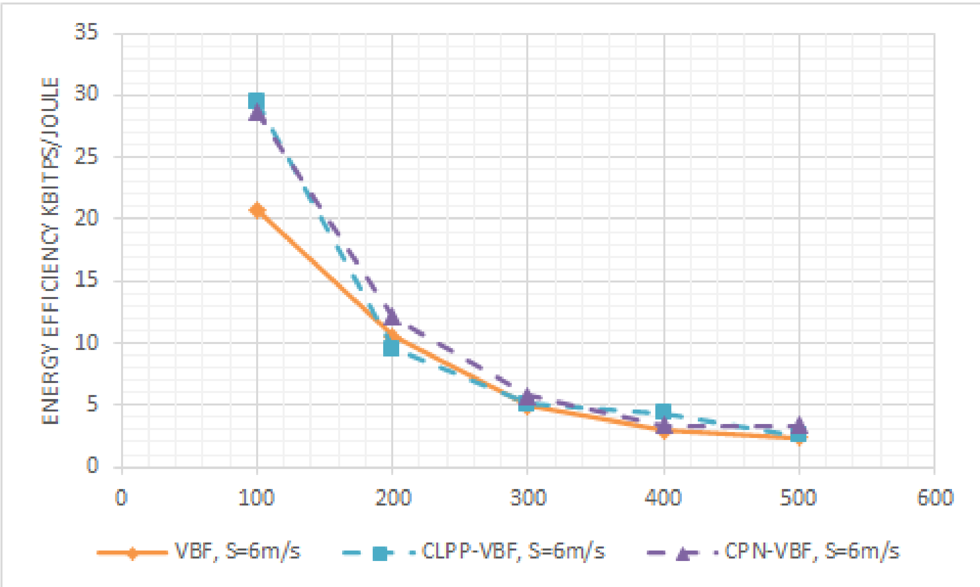

Figure 5.9 – *Energy Efficiency W =100 m, s= 6m/s*

the energy efficiency is related to the number of successful delivery data and it respective consumed energy, moreover the CPN-VBF has provided good result in PDR term and consumed less energy than VBF, hence it is obvious that it provides good energy efficiency over the VBF, in other hand CLPP-VBF does not provide good efficiency compared with CPN-VBF, for the reason that the protocol has consumed more energy in some instances, with a speed = 6 m/s, sensors are more prone to move away from their sender, CLPP-VBF prevent from future interruption probability and consume more energy with the mechanism of the forwarder discovery, that involves more sensor to forward data packet.

Following the figures 5.11 and 5.12, we can observe the efficiency of the proposed approaches compared with VBF, with a large radius pipeline = 200, a good energy efficiency means a good rate of delivery data with a less consumed energy, following the Figure 5.2 and 5.8, the successful delivery data packet are better than VBF for both protocols, with a less en-

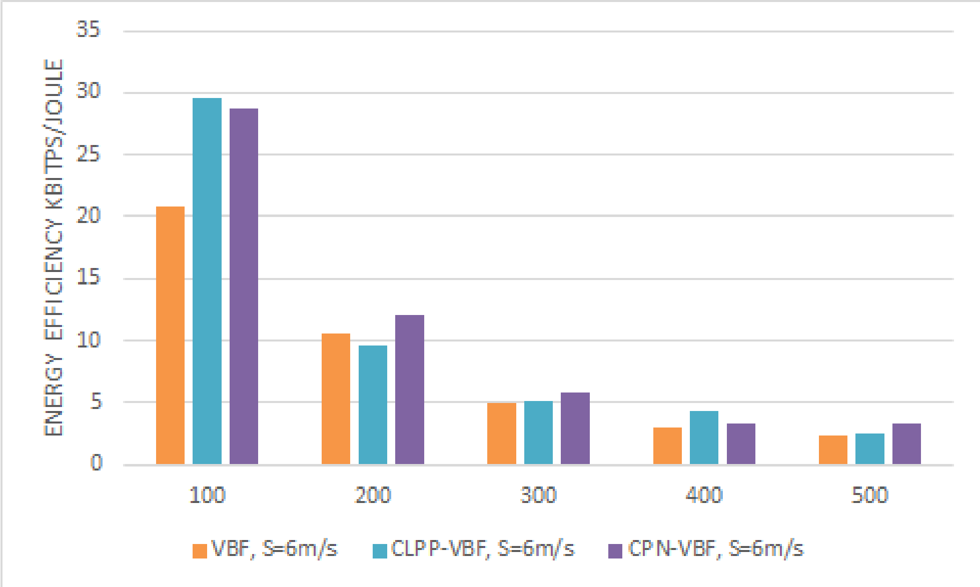

Figure 5.10 – *Energy Efficiency W =100 m, s= 6m/s*

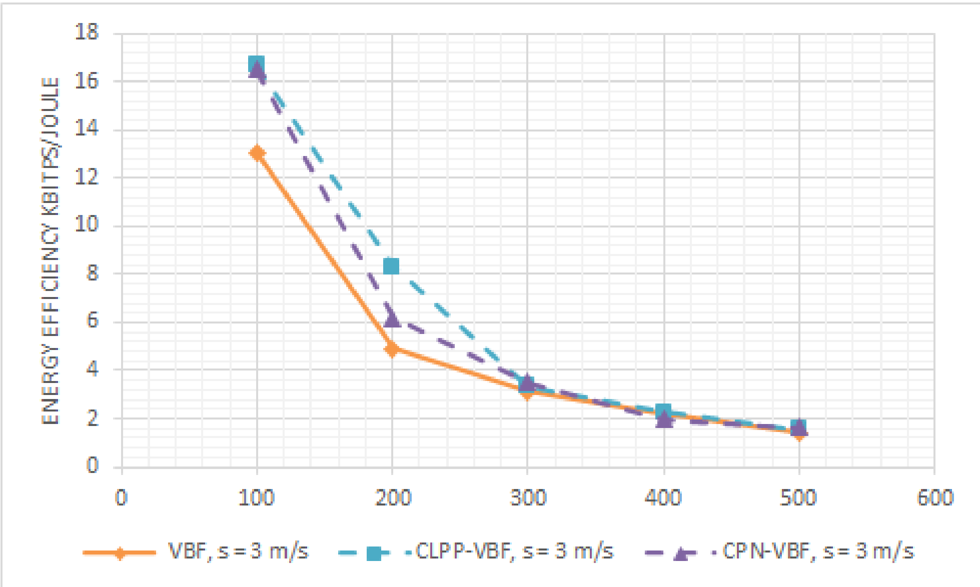

Figure 5.11 – *Energy Efficiency W =200 m, s= 3m/s*

ergy consumed as well, that significantly provides a good energy efficiency, though, according to the Figure 5.8 CPN-VBF has consumed more energy than the CLPP-VBF for the reasons explained before, however the protocol provides better results in term of PDR demonstrated in Figure 5.2, which has led to a better energy efficiency results.

5.1.4 Performance comparison

The following tables presents the performance comparison of the proposed protocols and VBF, where table 5.2 and 5.4 represents the gain of the obtained results in % for both protocol over the VBF, and the the table 5.3 and 5.5 illustrates the performance metric comparison as well

The table 5.2 summarizes the gain of CLPP-VBF and CPN-VBF with a radius pipeline = 100 and speed = 6 m/s compared with VBF, whereas the CLPP-VBF depicts a medium successful

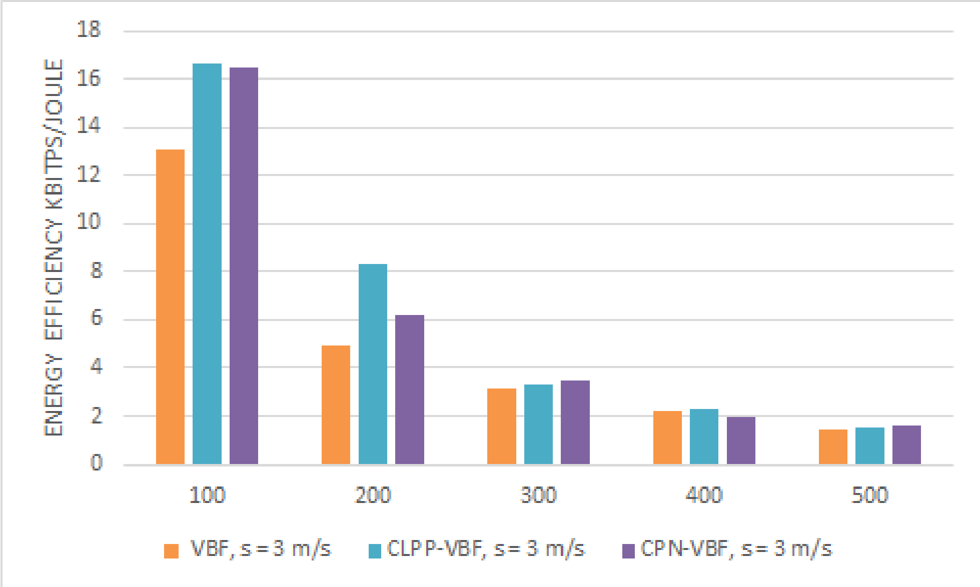

Figure 5.12 – *Energy Efficiency W =200 m, s= 3m/s*

Table 5.2 – *Performance results comparison W = 100 m, speed = 6 m/s*

Routing protocol	Packet Delivery Ratio	Average End to End Delay	Energy Consumption	Energy Efficiency
CLPP-VBF	6.18 %	6.41 %	25 %	29.82 %
CPN-VBF	9.65 %	9.22 %	23.27 %	27.84 %

delivery data according a to medium average delay, the saving energy and the efficiency are high, however the CPN-VBF has gained better results in term of delivery packet with a high reduced average delay and a medium consumed energy amount, the energy efficiency achieved is quite good. CPN-VBF provides better results in term of success rate compared with CLPP-VBF which has significantly consumed more energy, hence, CLPP-VBF has attempt more efficiency with 1.98 %.

The average delay is widely reduced compared with CLPP-VBF, as the overloaded nodes affect the average delay in such a way that data packet can be delayed due to the congestion of the nodes, it can induces more delay time, CPN-VBF prevent from sensors that receives a poor acoustic signal and avoid the transmission through it, hence more delay time is reduced.

We can conclude from both tables that the CPN-VBF outperform the CLPP-VBF with a speed = 6 m/s, since the proposed approach considers mobility and poor link quality due to multiple reasons, opposed to CLPP-VBF that considers only the mobility of sensors.

Table 5.3 – *Performance metrics comparison W = 100 m, speed = 6 m/s*

Routing protocol	Packet Delivery Ratio	Average End to End Delay	Energy Consumption	Energy Efficiency
VBF [Xie et al., 2006]	Low	Medium	Medium	Medium
CLPP-VBF	Medium	Medium	Low	High
CPN-VBF	High	Low	Medium	High

As it is depicting on the tables 5.4 and 5.5, the results demonstrates the gain of both protocols compared with VBF at radius pipeline = 200 m and speed = 3 m/s, CLPP-VBF shows a medium successful delivery data with a medium reduced delay as the saved energy is high according to a good efficiency, however CPN-VBF achieve a high delivery ratio compared with CLPP-VBF, with a large reduced delay, however it consumed energy is more than the CLPP-VBF, the mechanism provide a good energy efficiency.

The energy has been more consumed with CPN-VBF in a large pipeline, the reason is, a

Table 5.4 – *Performance result comparison W = 200 m, speed = 3 m/s*

Routing protocol	Packet Delivery Ratio	Average End to End Delay	Energy Consumption	Energy Efficiency
CLPP-VBF	4.54 %	5.81 %	11.73 %	21.44 %
CPN-VBF	5.06 %	6.97 %	7.11 %	20.77 %

Table 5.5 – *Performance metrics comparison W = 200 m, speed = 3 m/s*

Routing protocol	Packet Delivery Ratio	Average End to End Delay	Energy Consumption	Energy Efficiency
VBF [Xie et al., 2006]	Low	High	High	Low
CLPP-VBF	Medium	Medium	Low	High
CPN-VBF	High	Low	Medium	High

dense network involves multiple and duplicate data packet transmission, that induce node's overloading, where the overload decreases the remaining energy, the received acoustic signal is affected, hence the link quality is considered as poor, CPN-VBF detect such events and provide a mechanism that prevent from poor link quality, the operation of the protocol to measure the quality of link may consume more energy, in other hand it improves the success rate, that bring a high energy efficiency.

We can conclude that CLPP-VBF has a good network performance, however the CPN-VBF achieved a good performance with a large pipeline radius, despite the consumed energy. It has been demonstrated and proved that the method of Newton Interpolation is more accurate and gives better results than the Lagrange Interpolation [Srivastava et Srivastava, 2012, Yang et Gordon, 2016, Alkahtani, 2020], however, the Lagrange Interpolation polynomials have to be reevaluated each time y_i, hence the Lagrange polynomials are computationally demanding, compared with Newton Interpolation that uses the divided difference that is more computationally efficient [Shyu et Ytreberg, 2011].

Conslusion

This chapter has introduced a performance comparison between the proposed contributions in this thesis (CLPP-VBF and CPN-VBF) compared with the VBF routing protocol. The adopted method of the routing pipeline by the VBF protocol which allows only sensors near the vector to forward packet, enhances the performance of the network, and saves more energy, in addition the Self-adaptation algorithm redefine the policy of the forwarder selection, by taken into account the desirability of the sensors among it neighbors to forward, improves the efficiency of the protocol, hence the protocol presents numerous constraints, the pipeline radius may affect the routing performance when it does not contains quite number of sensors.

Sensor nodes inside the pipeline are continuously forwarding which significantly consuming more energy, in addition the protocol does not takes into consideration the acoustic link quality, nor re-transmit the lost data packet. This thesis has been focused on the acoustic link quality along with their failures probability, and the implementation has been made based on the VBF protocol in order to enhance and improve the protocol by targeting it main constraints. Two contributions based on the interpolation polynomial have been proposed, explained and summarized, with the aim to prevent from failures and poor acoustic link before selecting a node as a forwarder.

This chapter has provided a comparison study between the proposed contributions, where the obtained results are compared and explained according to the proposed metrics, the comparison depicted that CPN-VBF outperforms VBF and CLPP-VBF at different parameters such as radius and speed in term of delivery ratio, average delay and energy efficiency, for the reason that the approach has targeted not only the mobility but the link quality as well which increase it efficiency compared with CLPP-VBF, in addition, in mathematics aspect it has been proven that the Newton Interpolation polynomial brings more accuracy than the Lagrange Interpolation.

Scientific Contributions

International Journal

Ahmed, M. B., Cherif, M. A., Hacene, S. B. (2021). A Cross-Layer Predictive and Preemptive Routing Protocol for Underwater Wireless Sensor Networks Using the Lagrange Interpolation. International Journal of Wireless Networks and Broadband Technologies (IJWNBT), 10(2), 78-99.

National Communication

Ahmed, M. B., Cherif, M. A., Hacene, S. B. "The evolution of the Vector-Based Forwarding routing protocol in Underwater Wireless Sensor Network", ateliers SACONET, December 2019, Oran.

Ahmed, M. B., Cherif, M. A., Hacene, S. B. "A Cross-Layer protocol for a Non-Synchronous Localization Scheme in Large-scale Underwater Wireless Sensor Network", Journées Doctorales, 2019, Sidi Bel Abbes.

Conclusion

Throughout the last years the Underwater Wireless Sensor Network (UWSN) have became the enabling technology for the underwater environment exploration and have paid more intention of many scientific researchers, for the reason that those technology can afford numerous and various application to the scientific community, such as the aquatic environment monitoring, natural disturbances of the ocean, disaster prevention as seismic activity and many other benefits, despite the large advantages that the UWSN can bring to the human society, the technology presents some limits, as the marine environment is considered as a large scale, many factors can be encountered during the operation of those sensors, as the high propagation delay, high noises and the presence of some interference, battery depletion, the costly deployment, the localization challenge due to the 3-Dimensional deployment, the temporary losses of connectivity, void regions and limited bandwidth.

The achievement of an effective and optimal routing protocol that offers a better operation of the UWSN is a critical purpose for the researchers, where the underwater sensors have to communicate and transmit information in efficient way, although several protocols have targeted the challenges confronted by the marine sensors, as the energy constraints, mobility of sensors, the channel conditions, and void regions. Some of the marine factors have to be taken into consideration, as water current and the presence of noises and interference as the enormous rocks, ship and sensors can affect the received signal which conduct to a bad network performance.

Some of the existing routing mechanisms have been focused on the quality of the link between sensors within a network, in such a way that sensors have to evaluate the efficiency of the acoustic link before sending data, meanwhile some of others have discussed the problem of link disturbances and failure and have provided multiple mechanisms and methods to overcome those issues. The problem of the connectivity loss, deficiency link and communication interruption during data transmission is still discussed since the exploitation of the marine environment is still growing up, and the networks are getting bigger, we have been interested in this part of issue, by presenting some methods and mechanisms in order to avoid weak communication link and diminish the problem of link breakage and interruption problem.

Our proposed works have been implemented and elaborated using the well-known routing protocol for underwater sensors 'Vector Based Forwarding' (VBF), in order to bring some improvement to the protocol which presents some weaknesses and does not takes mainly into consideration the link quality as well, the main objective of this thesis is to design a localization routing protocol that operates in a cross-layer manner that allows the collaboration between the MAC-layer and the Network layer to determine and predict first if a future link failure will take place, or the existing communication link is too weak to make a data packet achieve the right destination and overcome as early as possible those problems.

We proposed two contributions to predict a weak communication link and the probability of their interruption, we have cited first some of the related works that have bring a certain good performance to avoid and prevent from faint communication within a network, but in other part they can presents also some demerits, which makes the main problem statement still addressed.

In our first contribution, we have introduced a method based on the Lagrange Interpolation, in order to predict and prevent from earlier future link failure problem due to the mobility of nodes in a major time. the Lagrange Interpolation formula has bring the advantage to differentiate between a sensor node that could leave it sender transmission range, or it could regain a closer position from it sender, this information is included on the forwarder selection policy where the sensor has to first check it link reliability with the sender before relying the data packet, in addition a rediscovering phase has been added to allow other candidates nodes that are more performing to take place, the purpose was to gain more delivered packets and reduce the delay time.

We demonstrated in the fourth chapter, a mechanism based on the Newton Interpolation formula to determine and evaluate the link reliability before a transmission can takes a place, meanwhile the approach allows to verify and distinguish two situations that can occurs, first, when the link have a high probability to interrupt due to the node mobility and water current that can makes the position of sensors inaccurate, while the second situation can occurs when sensor nodes have a low remaining energy and the presence of some interference can hardly affect and degrade the receiving signal, an important loss of data packet may results. Our method was implemented in a cross-layer mechanism, for the earlier detection and prediction from link failure problems, where a sender node has to evaluate the efficiency of the link before transmitting any data packet, the purpose was to avoid unnecessary transmission that consumes more energy.

The fifth chapter represents the performance comparison of the proposed contributions, where the obtained results are discussed and compared with VBF, using different parameters as radius pipeline and speed, and different scenarios according to different metrics. The comparison analyzes have proven the efficiency of both presented protocols, however it has been demonstrated that the proposed mechanism based on Newton Interpolation polynomials (CPN-VBF) bring better results and proves it efficiency compared with the mechanism that utilizes the Lagrange Interpolation (CLPP-VBF), in one hand, CPN-VBF has targeted not only the mobility of sensors, but the acoustic link efficiency and quality in addition, that strengthen the mechanism, moreover it has been demonstrated by several researchers that the Newton Interpolation formula is more accurate and reliable than the Lagrange Interpolation polynomial for computational reasons

We have approved our two contributions by using the Network Simulator (NS-2) using multiple and various scenarios, with a low and dense network, and high and low speed of sensors, the results have shown that the proposed contributions have bring an overall good performance of the simulation, we have discussed the obtained results through some metrics that we have presented and explained, we conclude then, that our mechanisms have improved the existing VBF routing protocol in term of the successful delivered data packet, a reduction of the end to end delay time, and finally, an overall saving energy and good efficiency.

Perspectives

Our proposed work has mainly addressed the probability of a future communication link failure or breakage during a transmission process within a given underwater sensor network, the designed mechanisms have proven their overall efficiency against the routing protocol VBF, hence, as a future work, we could improve both methods by taken into consideration more underwater factors that could be the reasons for unreliable communication link.

In the first mechanism proposed in the contribution 1 , the study was targeted the probability of a future link disturbances and breakage that can occurs due to the mobility of underwater sensors or even the water current, we have included a method that is aimed to discover another potential sensor node with which the link is more effective. As a future work we could improve more the routing protocol in term of energy consumption caused by the generated request packet for the rediscovering phase, in order to save more the overall network energy.

In the second mechanism proposed in the contribution 2, we focused our study on the wireless communication link with a low efficiency by taken into consideration the low residual energy and the presence of interference that can be the main reasons of a weak received signal, as a future work we could bring better performance results by considering more possible criterion that may generates a weak and deficiency communication link, and launching a process that might regain an optimal path leading to the sink, in order to enhance more the successful delivered data.

The fifth chapter introduce a performance comparison in order to evaluate the reliability of the proposed works, as a future perspective, we could consider more proposed works and protocols to provide an efficient comparison and analyzes of the proposed contributions. As a future works we could enhance both CPN-VBF and CLPP-VBF by taken into account the creation of the void regions and bring a method to by pass the void holes inside the routing pipeline, considerate the overloaded sensor nodes caused by the multiple forwarding and duplicate packet.

The use of the Network Simulator NS-2 with the Aqua-Sim packaging have enabled our study to evaluate the performance of the proposed works and afford us to obtain the achieved results by the simulation of the existing VBF routing protocol and our realized schemes, it would be useful for a future work and perspective to work with a credible environment for a better conception and outlook as the Network Simulator NS-3.

Bibliography

Claudia Jacy Barenco Abbas, Raphael Montandon, Ana Lucila Sandoval Orozco, et Luis Javier GarcíA Villalba. Ebvbf: energy balanced vector based forwarding protocol. *IEEE Access*, 7:54273–54284, 2019.

Kanika Agarwal et Nitin Rakesh. Node mobility issues in underwater wireless sensor network. Dans *Advances in Computer and Computational Sciences*, pages 293–303. Springer, 2017.

Mukhtiar Ahmed, Mazleena Salleh, et M Ibrahim Channa. Routing protocols based on node mobility for underwater wireless sensor network (uwsn): A survey. *Journal of Network and Computer Applications*, 78:242–252, 2017.

Ian F Akyildiz, Dario Pompili, et Tommaso Melodia. Challenges for efficient communication in underwater acoustic sensor networks. *ACM Sigbed Review*, 1(2):3–8, 2004.

Ian F Akyildiz, Dario Pompili, et Tommaso Melodia. Underwater acoustic sensor networks: research challenges. *Ad hoc networks*, 3(3):257–279, 2005.

Ian F Akyildiz, Dario Pompili, et Tommaso Melodia. State-of-the-art in protocol research for underwater acoustic sensor networks. Dans *Proceedings of the 1st ACM international workshop on Underwater networks*, pages 7–16, 2006.

Faisal Abdulaziz Alfouzan, Seyed Mohammad Ghoreyshi, Alireza Shahrabi, et Mahsa Sadeghi Ghahroudi. An auv-aided cross-layer mobile data gathering protocol for underwater sensor networks. *Sensors*, 20(17):4813, 2020.

Tariq Ali, Low Tang Jung, et Ibrahima Faye. Classification of routing algorithms in volatile environment of underwater wireless sensor networks. *International Journal of Communication Networks and Information Security*, 6(2):129, 2014.

Badr Saad T Alkahtani. A new numerical scheme based on newton polynomial with application to fractional nonlinear differential equations. *Alexandria Engineering Journal*, 59(4):1893–1907, 2020.

Amir Abdelkader AOUIZ. *Qualité de service dans les protocoles multi-chemins.* PhD thesis, University of Djillali Liabes, 2020.

Saeid Pourroostaei Ardakani. Data aggregation routing protocols in wireless sensor networks: A taxonomy. *arXiv preprint arXiv:1704.04588*, 2017.

Muhsin Atto. *Cross layer based protocols for energy aware and critical data delivery related applications using wireless sensor networks.* PhD thesis, University of Reading, 2016.

Khalid Mahmood Awan, Peer Azmat Shah, Khalid Iqbal, Saira Gillani, Waqas Ahmad, et Yunyoung Nam. Underwater wireless sensor networks: A review of recent issues and challenges. *Wireless Communications and Mobile Computing*, 2019, 2019.

Muhammad Ayaz, Imran Baig, Azween Abdullah, et Ibrahima Faye. A survey on routing techniques in underwater wireless sensor networks. *Journal of Network and Computer Applications*, 34(6):1908–1927, 2011.

Ke Bao, John D Matyjas, Fei Hu, et Sunil Kumar. Intelligent software-defined mesh networks with link-failure adaptive traffic balancing. *IEEE Transactions on Cognitive Communications and Networking*, 4(2):266–276, 2018.

Stefano Basagni, Chiara Petrioli, Roberto Petroccia, et Daniele Spaccini. Carp: A channel-aware routing protocol for underwater acoustic wireless networks. *Ad Hoc Networks*, 34:92–104, 2015.

Syed Abdul Basit et Manoj Kumar. A review of routing protocols for underwater wireless sensor networks. *International Journal of Advanced Research in Computer and Communication Engineering*, 4(12):373–378, 2015.

Souad Benabdallah et Kelthoum Hammad. Le routage dans les réseaux de capteurs sous-marins, 2013.

Mukesh Beniwal, Rishi Pal Singh, et Anju Sangwan. A localization scheme for underwater sensor networks without time synchronization. *Wireless Personal Communications*, 88(3):537–552, 2016.

Mukesh Beniwal et Rishipal Singh. Localization techniques and their challenges in underwater wireless sensor networks. *Int. J. Comput. Sci. Inf. Technol*, 5:4706–4710, 2014.

Imane Benkhelifa, Nadia Nouali-Taboudjemat, et Samira Moussaoui. Disaster management projects using wireless sensor networks: An overview. Dans *2014 28th International Conference on Advanced Information Networking and Applications Workshops*, pages 605–610. IEEE, 2014.

Himanshi Bhambri et Abhishek Swaroop. Underwater sensor network: Architectures, challenges and applications. Dans *2014 International Conference on Computing for Sustainable Global Development (INDIACom)*, pages 915–920. IEEE, 2014.

Nahayo NDINDAYINO Blaise-Patrick. *Comparative Analysis of Single-path Vs Multipath routing: a Case Study of AODV and AOMDV Protocols*. PhD thesis, JECRC University, 2017.

Safdar Hussain Bouk, Syed Hassan Ahmed, et Dongkyun Kim. Delay tolerance in underwater wireless communications: A routing perspective. *Mobile Information Systems*, 2016, 2016.

Sofiane Boukli-Hacene, Ouali Abdelkader, et Bassou Asmaa. Predictive preemptive certificate transfer in cluster-based certificate chain. *International Journal of Communication Networks and Information Security*, 6(1):44, 2014.

Britannica. Interpolation. https://www.britannica.com/science/interpolation, Octobre 2016.

Keyu Chen, Maode Ma, En Cheng, Fei Yuan, et Wei Su. A survey on mac protocols for underwater wireless sensor networks. *IEEE Communications Surveys & Tutorials*, 16(3):1433–1447, 2014.

Chien-Fu Cheng et Lung-Hao Li. Data gathering problem with the data importance consideration in underwater wireless sensor networks. *Journal of Network and Computer Applications*, 78:300–312, 2017.

Alejandro De Gante, Mohamed Aslan, et Ashraf Matrawy. Smart wireless sensor network management based on software-defined networking. Dans *2014 27th Biennial Symposium on Communications (QBSC)*, pages 71–75. IEEE, 2014.

Sarang C Dhongdi, Pritish Nahar, Rishabh Sethunathan, Lucy J Gudino, et KR Anupama. Cross-layer protocol stack development for three-dimensional underwater acoustic sensor network. *Journal of Network and Computer Applications*, 92:3–19, 2017.

Roee Diamant, Lars Michael Wolff, et Lutz Lampe. Location tracking of ocean-current-related underwater drifting nodes using doppler shift measurements. *IEEE Journal of Oceanic Engineering*, 40(4):887–902, 2014.

Mari Carmen Domingo. Overview of channel models for underwater wireless communication networks. *Physical Communication*, 1(3):163–182, 2008.

Umar Draz, Tariq Ali, Sana Yasin, Umair Waqas, et Usman Rafiq. Towards formalism of link failure detection algorithm for wireless sensor and actor networks. Dans *2019 International Conference on Engineering and Emerging Technologies (ICEET)*, pages 1–6. IEEE, 2019.

S El-Rabaie, D Nabil, R Mahmoud, et Mohammed A Alsharqawy. Underwater wireless sensor networks (uwsn), architecture, routing protocols, simulation and modeling tools, localization, security issues and some novel trends. *Netw. Commun. Eng*, 7(8):335–354, 2015.

Melike Erol et Sema Oktug. A localization and routing framework for mobile underwater sensor networks. Dans *IEEE INFOCOM Workshops 2008*, pages 1–3. IEEE, 2008.

Melike Erol-Kantarci, Sema Oktug, Luiz Vieira, et Mario Gerla. Performance evaluation of distributed localization techniques for mobile underwater acoustic sensor networks. *Ad Hoc Networks*, 9(1):61–72, 2011.

Salmah Fattah, Abdullah Gani, Ismail Ahmedy, Mohd Yamani Idna Idris, et Ibrahim Abaker Targio Hashem. A survey on underwater wireless sensor networks: Requirements, taxonomy, recent advances, and open research challenges. *Sensors*, 20(18):5393, 2020.

Emad Felemban, Faisal Karim Shaikh, Umair Mujtaba Qureshi, Adil A Sheikh, et Saad Bin Qaisar. Underwater sensor network applications: A comprehensive survey. *International Journal of Distributed Sensor Networks*, 11(11):896832, 2015.

Baoru Gao, Ling Zhang, Dongsheng Chu, Jiucai Jin, et Lanjun Liu. A novel mobility aware medium access control protocol for underwater sensor networks. Dans *OCEANS 2016-Shanghai*, pages 1–6. IEEE, 2016.

Chris Giantsis et Anastasios A Economides. Comparison of routing protocols for underwater sensor networks: a survey. *International Journal of Communication Networks and Distributed Systems*, 7(3-4):192–228, 2011.

Nitin Goyal, Mayank Dave, et Anil K Verma. Data aggregation in underwater wireless sensor network: Recent approaches and issues. *Journal of King Saud University-Computer and Information Sciences*, 31(3):275–286, 2019.

Nitin Goyal, Mayank Dave, et Anil Kumar Verma. A novel fault detection and recovery technique for cluster-based underwater wireless sensor networks. *International Journal of Communication Systems*, 31(4):e3485, 2018.

Ruolin Guo, Danyang Qin, Min Zhao, et Guangchao Xu. Mobile target localization based on iterative tracing for underwater wireless sensor networks. *International Journal of Distributed Sensor Networks*, 16(7):1550147720940634, 2020.

Sanjeev Kumar Gupta et Poonam Sinha. Overview of wireless sensor network: a survey. *Telos*, 3(15μW):38mW, 2014.

Taimur Hafeez, Nadeem Javaid, Ahmad Raza Hameed, Arshad Sher, Zahoor Ali Khan, et Umar Qasim. Avn-ahh-vbf: Avoiding void node with adaptive hop-by-hop vector based forwarding for underwater wireless sensor networks. Dans *2016 10th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS)*, pages 49–56. IEEE, 2016.

Guangjie Han, Jinfang Jiang, Lei Shu, Yongjun Xu, et Feng Wang. Localization algorithms of underwater wireless sensor networks: A survey. *Sensors*, 12(2):2026–2061, 2012.

Shuai Han, Jin Yue, Weixiao Meng, et Xuanli Wu. A localization based routing protocol for dynamic underwater sensor networks. Dans *2016 IEEE Global Communications Conference (GLOBECOM)*, pages 1–6. IEEE, 2016.

Md Farhad Hossain, Musbiha Binte Wali, Kumudu S Munasinghe, et Abbas Jamalipour. Three dimensional (3d) underwater sensor network architectures for intruder localization using em wave. Dans *2016 IEEE Wireless Communications and Networking Conference*, pages 1–6. IEEE, 2016.

Eng Dina Mahmoud Ibrahim Hussein. *Modelling and Performance Enhancement of Underwater Wireless Sensor Networks by Petri Nets*. PhD thesis, Faculty of Engineering, Tanta University, 2014.

Teerawat Issariyakul et Ekram Hossain. Introduction to network simulator 2 (ns2). Dans *Introduction to network simulator NS2*, pages 1–18. Springer, 2009.

Kavita Jaiswal et Veena Anand. Eomr: an energy-efficient optimal multi-path routing protocol to improve qos in wireless sensor network for iot applications. *Wireless Personal Communications*, 111(4):2493–2515, 2020.

Mohammed Jouhari, Khalil Ibrahimi, Hamidou Tembine, et Jalel Ben-Othman. Underwater wireless sensor networks: A survey on enabling technologies, localization protocols, and internet of underwater things. *IEEE Access*, 7:96879–96899, 2019.

Abu Raihan M Kamal, Chris J Bleakley, et Simon Dobson. Failure detection in wireless sensor networks: A sequence-based dynamic approach. *ACM Transactions on Sensor Networks (TOSN)*, 10(2):1–29, 2014.

Bhanu Kishore Kamapantula. Muti-metric adaptive routing algorithm for underwater wireless sensor networks. Dans *Texas A&M University-Corpus Christi Corpus Christi*. 2011.

T Kavitha et D Sridharan. Security vulnerabilities in wireless sensor networks: A survey. *Journal of information Assurance and Security*, 5(1):31–44, 2010.

Lucia Keleadile Ketshabetswe, Adamu Murtala Zungeru, Mmoloki Mangwala, Joseph M Chuma, et Boyce Sigweni. Communication protocols for wireless sensor networks: A survey and comparison. *Heliyon*, 5(5):e01591, 2019.

Muhammad Khalid, Farah Ahmad, Muhammad Arshad, Waqar Khalid, Naveed Ahmad, et Yue Cao. E2mr: energy-efficient multipath routing protocol for underwater wireless sensor networks. *IET Networks*, 8(5):321–328, 2019.

Muhammad Khalid, Zahid Ullah, Naveed Ahmad, Muhammad Arshad, Bilal Jan, Yue Cao, et Awais Adnan. A survey of routing issues and associated protocols in underwater wireless sensor networks. *Journal of Sensors*, 2017, 2017.

Anwar Khan, Ihsan Ali, Abdullah Ghani, Nawsher Khan, Mohammed Alsaqer, Atiq Ur Rahman, et Hasan Mahmood. Routing protocols for underwater wireless sensor networks: Taxonomy, research challenges, routing strategies and future directions. *Sensors*, 18(5):1619, 2018.

Hashim Khan, Syed Ali Hassan, et Haejoon Jung. On underwater wireless sensor networks routing protocols: A review. *IEEE Sensors Journal*, 20(18):10371–10386, 2020.

Ahmad Khasawneh, Muhammad Shafie Bin Abd Latiff, Omprakash Kaiwartya, et Hassan Chizari. A reliable energy-efficient pressure-based routing protocol for underwater wireless sensor network. *Wireless Networks*, 24(6):2061–2075, 2018.

Ahmad M Khasawneh, Omprakash Kaiwartya, Jaime Lloret, Hayfa Y Abuaddous, Laith Abualigah, Mohammad Al Shinwan, Mahmoud Ahmad Al-Khasawneh, Marwan Mahmoud, et Rupak Kharel. Green communication for underwater wireless sensor networks: Triangle metric based multi-layered routing protocol. *Sensors*, 20(24):7278, 2020.

Sangeeta Kumari, Pavan Kumar Mishra, et Veena Anand. Fault resilient routing based on moth flame optimization scheme for underwater wireless sensor networks. *Wireless Networks*, 26 (2):1417–1431, 2020.

Tanya Le Sage, Axel Bindel, Paul Conway, Sian Slawson, et Andrew West. Development of a wireless sensor network for embedded monitoring of human motion in a harsh environment. Dans *2011 IEEE 3rd International Conference on Communication Software and Networks*, pages 112–115. IEEE, 2011.

Sangho Lee et Kiseon Kim. Localization with a mobile beacon in underwater sensor networks. Dans *2010 IEEE/IFIP International Conference on Embedded and Ubiquitous Computing*, pages 316–319. IEEE, 2010.

Ning Li, José-Fernán Martínez, Juan Manuel Meneses Chaus, et Martina Eckert. A survey on underwater acoustic sensor network routing protocols. *Sensors*, 16(3):414, 2016.

Jun Liu, Zhaohui Wang, Jun-Hong Cui, Shengli Zhou, et Bo Yang. A joint time synchronization and localization design for mobile underwater sensor networks. *IEEE Transactions on Mobile Computing*, 15(3):530–543, 2015.

Yao Lu, Jianping Chen, Ioan Sorin Comsa, et Pierre Kuonen. Backup path with energy prediction based on energy-aware spanning tree in wireless sensor networks. Dans *2013 International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery*, pages 392–397. IEEE, 2013.

Junhai Luo, Liying Fan, Shan Wu, et Xueting Yan. Research on localization algorithms based on acoustic communication for underwater sensor networks. *Sensors*, 18(1):67, 2018.

Junhai Luo, Yang Yang, Zhiyan Wang, Yanping Chen, et Man Wu. A mobility-assisted localization algorithm for three-dimensional large-scale uwsns. *Sensors*, 20(15):4293, 2020.

Muhammet Macit, V Cagri Gungor, et Gurkan Tuna. Comparison of qos-aware single-path vs. multi-path routing protocols for image transmission in wireless multimedia sensor networks. *Ad hoc networks*, 19:132–141, 2014.

Shiwen Mao. Chapter 8 - fundamentals of communication networks. Dans Alexander M. Wyglinski, Maziar Nekovee, et Y. Thomas Hou, éditeurs, *Cognitive Radio Communications and Networks*, pages 201–234. Academic Press, Oxford, 2010. ISBN 978-0-12-374715-0. URL https://www.sciencedirect.com/science/article/pii/B9780123747150000083.

Yuxin Mao et Ping Zhu. A source-initiated on-demand routing algorithm based on the thorup-zwick theory for mobile wireless sensor networks. *The Scientific World Journal*, 2013, 2013.

Padmini Misra. Routing protocols for ad hoc mobile wireless networks. *Courses Notes, available at http://www. cis. ohio-state. edu/~ jain/cis788-99/adhoc_routing/index. html*, 1999.

Reza Mohamaddoust, Abolfazl Toroghi Haghighat, Mohamad Javad Motahari Sharif, et Niccolo Capanni. A novel design of an automatic lighting control system for a wireless sensor network with increased sensor lifetime and reduced sensor numbers. *Sensors*, 11(9):8933–8952, 2011.

Marjan Moradi, Javad Rezazadeh, et Abdul Samad Ismail. A reverse localization scheme for underwater acoustic sensor networks. *Sensors*, 12(4):4352–4380, 2012.

Kyengheum Na, Heungwoo Nam, et Sunshin An. The architecture of surface gateway and its base station for underwater wireless sensor network. Dans *2011 IFIP 9th International Conference on Embedded and Ubiquitous Computing*, pages 442–445. IEEE, 2011.

Sabrine Naimi. *Gestion de la mobilité dans les réseaux Ad Hoc par anticipation des métriques de routage*. PhD thesis, University of Paris Sud-Paris XI; Engineering School of Tunis (Tunisie), 2015.

Padmalaya Nayak et Bhavani Vathasavai. Impact of random mobility models for reactive routing protocols over manet. *International Journal of Simulation–Systems, Science & Technology*, 17 (34):112–115, 2016.

Pradeep Nazareth et BR Chandavarkar. Link quality-based routing protocol for underwater acoustic sensor networks. Dans *2020 11th International Conference on Computing, Communication and Networking Technologies (ICCCNT)*, pages 1–6. IEEE, 2020.

Paulo Neves, Michal Stachyra, et Joel Rodrigues. Application of wireless sensor networks to healthcare promotion. *Journal of Communications Software and Systems*, 4(3):181–190, 2008.

Nicolas Nicolaou, Andrew See, Peng Xie, Jun-Hong Cui, et Dario Maggiorini. Improving the robustness of location-based routing for underwater sensor networks. Dans *Oceans 2007-Europe*, pages 1–6. IEEE, 2007.

Bijan Paul, Md Ibrahim, Md Bikas, et Abu Naser. Vanet routing protocols: Pros and cons. *arXiv preprint arXiv:1204.1201*, 2012.

Roberto Petroccia, Konstantinos Pelekanakis, Joao Alves, Stefano Fioravanti, Stephane Blouin, et Sean Pecknold. An adaptive cross-layer routing protocol for underwater acoustic networks. Dans *2018 fourth underwater communications and networking conference (UComms)*, pages 1–5. IEEE, 2018.

Dario Pompili, Tommaso Melodia, et Ian F Akyildiz. Three-dimensional and two-dimensional deployment analysis for underwater acoustic sensor networks. *Ad Hoc Networks*, 7(4):778–790, 2009.

Junaid Qadar, Anwar Khan, et Hasan Mahmood. Dnar: Depth and noise aware routing for underwater wireless sensor networks. Dans *Conference on Complex, Intelligent, and Software Intensive Systems*, pages 240–251. Springer, 2018.

Wang Qingwen, Cao Fei, Li Zhi, et Qi Qian. A novel efficient forwarding protocol for 3-d underwater wireless sensor networks. Dans *2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA)*, pages 506–509. IEEE, 2016.

Purobi Rahman. Efficient mac protocol for handling triple hidden terminal problems of multi-channel underwater sensor networks. 2017.

R Raj Priyadarshini et N Sivakumar. Enhancing coverage and connectivity using energy prediction method in underwater acoustic wsn. *Journal of Ambient Intelligence and Humanized Computing*, 11(7):2751–2760, 2020.

D. Rajendra Prasad, B. Kiran Kumar, et S. Indraneel. Mobility in wireless sensor networks. Dans Jennifer S. Raj, Abul Bashar, et S. R. Jino Ramson, éditeurs, *Innovative Data Communication Technologies and Application*, pages 165–171, Cham, 2020. Springer International Publishing.

Rasika S Ransing et Manita Rajput. Smart home for elderly care, based on wireless sensor network. Dans *2015 International Conference on Nascent Technologies in the Engineering Field (ICNTE)*, pages 1–5. IEEE, 2015.

Priyanka Rawat, Kamal Deep Singh, Hakima Chaouchi, et Jean Marie Bonnin. Wireless sensor networks: a survey on recent developments and potential synergies. *The Journal of supercomputing*, 68(1):1–48, 2014.

Yongji Ren, Jianlin Zhong, Jun Huang, Yanbo Song, Xuguang Xin, Ning Yu, et Renjian Feng. Orthogonal regression based multihop localization algorithm for large-scale underwater wireless sensor networks. *International Journal of Distributed Sensor Networks*, 10(3):596082, 2014.

Subrata Sahana, Karan Singh, Rajesh Kumar, et Sanjoy Das. A review of underwater wireless sensor network routing protocols and challenges. *Next-generation networks*, pages 505–512, 2018.

Umar Sani et Mohd Murtadha Mohamad. Green-centric communication void avoidance for underwater wireless sensor networks. *European Journal of Molecular & Clinical Medicine*, 7(3): 745–759, 2020.

Noman Shabbir et Syed Rizwan Hassan. Routing protocols for wireless sensor networks (wsns). *Wireless Sensor Networks-Insights and Innovations*, 2017.

Rukhsar Begum Shaikh et Abid H Sayed. Sensor node failure detection in wireless sensor network: A survey. *International Journal of Emerging Technology in Computer Science Electronics (IJETCSE)*, 14(2):72–74, 2015.

Conrad Shyu et F Marty Ytreberg. Accurate estimation of solvation free energy using polynomial fitting techniques. *Journal of computational chemistry*, 32(1):134–141, 2011.

Rupinder Singh, Jatinder Singh, et Ravinder Singh. Attacks in wireless sensor networks : a survey. Dans *International Journal of Computer Science and Mobile Computing*, pages 10–16, 2016.

NN Soreide, CE Woody, et SM Holt. Overview of ocean based buoys and drifters: present applications and future needs. Dans *MTS/IEEE Oceans 2001. An Ocean Odyssey. Conference Proceedings (IEEE Cat. No. 01CH37295)*, volume 4, pages 2470–2472. IEEE, 2001.

Raja B Srivastava et Purushottam Kumar Srivastava. Comparison of lagrange's and newton's interpolating polynomials. *Journal of Experimental Sciences*, 3(1), 2012.

Kuo-Feng Ssu, Chia-Ho Ou, et Hewijin Christine Jiau. Localization with mobile anchor points in wireless sensor networks. *IEEE transactions on Vehicular Technology*, 54(3):1187–1197, 2005.

Milica Stojanovic. On the relationship between capacity and distance in an underwater acoustic communication channel. *ACM SIGMOBILE Mobile Computing and Communications Review*, 11 (4):34–43, 2007.

Xin Su, Inam Ullah, Xiaofeng Liu, et Dongmin Choi. A review of underwater localization techniques, algorithms, and challenges. *Journal of Sensors*, 2020, 2020.

R Swetha, V Santhosh Amarnath, et VS Anitha Sofia. Wireless sensor network: a survey. *International Journal of Advanced Research in Computer and Communication Engineering*, pages 2292–2330, 2018.

H-P Tan, Adriana Felicia Gabor, Zhi Ang Eu, et Winston Khoon Guan Seah. A wide coverage positioning system (wps) for underwater localization. Dans *2010 IEEE International Conference on Communications*, pages 1–5. IEEE, 2010.

Hwee-Pink Tan, Roee Diamant, Winston KG Seah, et Marc Waldmeyer. A survey of techniques and challenges in underwater localization. *Ocean Engineering*, 38(14-15):1663–1676, 2011.

Gurkan Tuna. Clustering-based energy-efficient routing approach for underwater wireless sensor networks. *International Journal of Sensor Networks*, 27(1):26–36, 2018.

Iuliu Vasilescu, Keith Kotay, Daniela Rus, Matthew Dunbabin, et Peter Corke. Data collection, storage, and retrieval with an underwater sensor network. Dans *Proceedings of the 3rd international conference on Embedded networked sensor systems*, pages 154–165, 2005.

Adnan Walayat, Nadeem Javaid, Mariam Akbar, et Zahoor Ali Khan. Mees: Mobile energy efficient square routing for underwater wireless sensor networks. Dans *2017 IEEE 31st International Conference on Advanced Information Networking and Applications (AINA)*, pages 292–297. IEEE, 2017.

Hao Wang, Shilian Wang, Renfei Bu, et Eryang Zhang. A novel cross-layer routing protocol based on network coding for underwater sensor networks. *Sensors*, 17(8):1821, 2017.

Thomas Watteyne, Isabelle Augé-Blum, Mischa Dohler, Dominique Barthel, et France Meylan. Probabilité de collision lors du choix du noeud relais sans connaissance du voisinage dans un réseau de capteurs. Dans *IRAMUS Workshop, Poster Session, Val Thorens, France*, 2007.

Lian-suo Wei, Yuan Guo, et Shao-bin Cai. Mac protocol for underwater acoustic sensor network based on belied state space. *EURASIP Journal on Wireless Communications and Networking*, 2018 (1):1–8, 2018.

S Witman. Detecting gas leaks with autonomous underwater vehicles. *J Geophys Res Ocean*, pages 5458–5467, 2017.

Peng Xie, Jun-Hong Cui, et Li Lao. Vbf: vector-based forwarding protocol for underwater sensor networks. Dans *International conference on research in networking*, pages 1216–1221. Springer, 2006.

Peng Xie, Zhong Zhou, Zheng Peng, Hai Yan, Tiansi Hu, Jun-Hong Cui, Zhijie Shi, Yunsi Fei, et Shengli Zhou. Aqua-sim: An ns-2 based simulator for underwater sensor networks. Dans *OCEANS 2009*, pages 1–7. IEEE, 2009.

Ming Xu, Guangzhong Liu, Huafeng Wu, et Wei Sun. Towards robust routing in three-dimensional underwater wireless sensor networks. *International Journal of Distributed Sensor Networks*, 9(11):481570, 2013.

Yajun Yang et Sheldon P Gordon. Visualizing and understanding the components of lagrange and newton interpolation. *PRIMUS*, 26(1):39–52, 2016.

Haitao Yu, Nianmin Yao, et Jun Liu. An adaptive routing protocol in underwater sparse acoustic sensor networks. *Ad Hoc Networks*, 34:121–143, 2015.

Rahman Zandi, Mahmoud Kamarei, et Hadi Amiri. Distributed estimation of sensors position in underwater wireless sensor network. *International Journal of Electronics*, 103(5):853–867, 2016.

Zhaoquan Zeng. *A survey of underwater wireless optical communication*. PhD thesis, University of British Columbia, 2015.

Nusrat Zerin Zenia, Mohammed Aseeri, Muhammad R Ahmed, Zamshed I Chowdhury, et M Shamim Kaiser. Energy-efficiency and reliability in mac and routing protocols for underwater wireless sensor network: A survey. *Journal of Network and Computer Applications*, 71: 72–85, 2016.

Yi Zhou, Jianhua He, Kai Chen, Jianbo Chen, et Alei Liang. An area localization scheme for large scale underwater wireless sensor networks. Dans *2009 WRI International Conference on Communications and Mobile Computing*, volume 1, pages 543–547. IEEE, 2009.

Zhong Zhou, Jun-Hong Cui, et Shengli Zhou. Efficient localization for large-scale underwater sensor networks. *Ad Hoc Networks*, 8(3):267–279, 2010.

Sanfeng Zhu, Naigao Jin, Lei Wang, Xueshu Zheng, Shuailing Yang, et Ming Zhu. A novel dual-hydrophone localization method in underwater sensor networks. Dans *2016 IEEE/OES China Ocean Acoustics (COA)*, pages 1–4. IEEE, 2016.

Chaima Zidi. *Energy efficient underwater acoustic sensor networks*. PhD thesis, University of Sorbonne Paris Cité, 2018.

Amir Ehsani Zonouz, Liudong Xing, Vinod M Vokkarane, et Yan Lindsay Sun. A time-dependent link failure model for wireless sensor networks. Dans *2014 Reliability and Maintainability Symposium*, pages 1–7. IEEE, 2014.

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ملخص

تتكون شبكة الاستشعار اللاسلكية تحت الماء من عدد كبير من عقد الاستشعار والمركبات المنتشرة والموزعة تحت الماء ، باستخدام وسيط اتصال صوتي ثنائي الاتجاه. تجد هذه المستشعرات تطبيقاتها في استخدامات مختلفة مثل الجيش والمراقبة ، واكتشاف الألغام ، ومراقبة التلوث ، والوقاية من الكوارث الطبيعية ، والشعاب المرجانية ومراقبة موائل الحياة البحرية. نظرًا لانخفاض سرعة الانتشار الصوتي وقيود الطاقة والنطاق الترددي وتوهين الإشارة وامتصاصها والتداخل والضوضاء ، فقد تم إيلاء اهتمام خاص وتم اقتراح الكثير من الأبحاث وتصميمها لتحسين أداء الشبكة تحت الماء. الهدف الرئيسي من هذه الأطروحة هو اقتراح بروتوكول توجيه عبر الطبقات لشبكات الاستشعار اللاسلكية تحت الماء التي تتعاون بين التحكم في الوصول المتوسط وطبقة الشبكة ، من أجل تقييم كفاءة الارتباط الصوتي ، ومنع وتوقع الاحتمالات المستقبلية لفشل الوصلة و مشاكل الانقطاع بسبب ظروف البيئة المختلفة تحت الماء.

Resumé

Un réseau de capteurs sans fil sous-marin se compose d'un nombre important de nœuds de capteurs et de véhicules déployés et répartis sous l'eau, en utilisant un moyen de communication acoustique bidirectionnel. Ces capteurs trouvent leurs applications dans différents domaines tels que l'armée et la surveillance, la détection des mines, la surveillance de la pollution, la prévention des catastrophes naturelles, la surveillance des récifs coralliens et des habitats marins. En raison de la faible vitesse de propagation acoustique, des contraintes d'énergie et de bande passante, de l'atténuation et de l'absorption des signaux, des interférences et des bruits, une attention particulière a été portée et de nombreuses recherches ont été proposées et conçues pour optimiser les performances des réseaux sous-marins. L'objectif principal de cette thèse est de proposer un protocole de routage intercouche pour les réseaux de capteurs sans fil sous-marins qui coopère entre le contrôle d'accès au support et la couche réseau, afin d'évaluer l'efficacité de la liaison acoustique, de prévenir et de prédire la probabilité future de défaillances de la liaison et les problèmes d'interruption dû aux diverses conditions de l'environnement sous-marin.

Abstract

An Underwater Wireless Sensor Network (UWSN) consists of a significant number of sensor nodes and vehicles deployed and distributed underwater, using a two-way acoustic communication medium. These sensors find their applications in different uses such as military and surveillance, mine detection, pollution monitoring, natural disasters prevention, coral reef and marine life habitat monitoring. Due to the low acoustic propagation speed, energy and bandwidth constraints, signal attenuation and absorption, interference and noises, particular attention has been paid and plenty of researches has been proposed and designed to optimize the underwater network performances. The main objective of this thesis is to propose a cross-layer routing protocol for underwater wireless sensor networks that cooperate between the Medium Access Control and the Network layer, in order to evaluate the acoustic link efficiency, prevent and predict future probability of link failures and interruption problems due to various underwater environment conditions.