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Author: Ljubisav Jakovljević	……………………………………… (signature author)
Faculty supervisor: Erdal Cayirci External supervisor: Tore Idsøe	
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Wireless Seabed to Surface Communication for Real-Time Operations

by

Ljubisav Jakovljević

Supervisors:

Erdal Cayirci

Tore Idsøe

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I dedicate this thesis to Zorana Stanišić and my beloved family.

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Abstract

Wireless Seabed to Surface Communication for real-time operations is a research project intended to develop a new solution for Halliburton subsea operation. The project goal is to provide a reliable solution for real-time pipeline monitoring in the harsh underwater environment. The solution can be invaluable for oil and gas companies by reducing the cost of pipeline monitoring and ensuring pipeline security. This thesis aims to develop a reliable and cheap solution that will replace the current one. To design a solution that needs to be reliable, robust and ready-to-use, commercial off-the-shelf equipment will be used.

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Acronyms:

ACK	Acknowledgment
ARQ	Automatic Repeat reQuest
ALOHAnet	Additive Links On-line Hawaii Area Network
UWSN	Underwater Wireless Sensor Network
UASN	Underwater Acoustic Sensor Network
NS2	Network Simulator 2
OS	Operation System
OTcl	Object-oriented Tools Command language
LAN	Local Area Network
WAN	Wide Area Network
NS-Miracle	Network Simulator- Multi-InteRfAce Cross-Layer Extension
MAC	Media Access Control
OSI	Open Systems Interconnection
FDMA	Frequency-division Multiple Access
CDMA	Code-division Multiple Access
TDMA	Time-division Multiple Access
CSMA	Carrier Sense Multiple Access
WSN	Wireless Sensor Network

ROV	Remote Operated Vehicles
COTS	Commercial off-the-shelf
SUNSET	The Sapienza University Networking framework for underwater Simulation, Emulation and real-life Testing
DESERT	DEsign, Simulate, Emulate and Realize Test-beds for Underwater network protocols
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
RTS	Request to Send
CTS	Clear to Send
GEO	Geostationary Earth Orbit
MEO	Medium Earth Orbit
LEO	Low Earth Orbit
ISL	Inter-Satellite Links
UML	Mobile Users Links
GWL	Gateway Links
LOS	Line of the Site
RAI	RadioActive Isotope
SHF	Super High Frequency
MSS	Mobile Satellite Services
BSS	Broadcast Satellite Service
FSS	Fixed Satellite Service
GPS	Global Positioning System
RF	Radio Frequency
CRC	Cyclic Redundancy Check
DSSS	Direct-Sequence Spread Spectrum

MFSK	Multiple Frequency-Shift Keying
PSK	Phase-Shift Keying
S2C	Sweep-Spread Carrier
FEC	Forward Error Correction
OFDM	Orthogonal Frequency Division Multiplexing
PVC	Polyvinyl Chloride
BASS	Broadband Acoustic Spread Spectrum
VHF	Very High Frequency
UHF	Ultra High Frequency
GSM	Global System for Mobile Telecommunications
M2M	Machine to Machine
ISI	Inter Signal Interference
SBC	Single Board Computers
ISM	Industrial, Scientific and Medical band
SBD	Short Burst Data
SMS	Short Message Service
CSD	Circuit Switched Data
FCS	Frame Check Sequence
SFD	Start Frame Delimiter

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1. Introduction

Oil companies are always looking for new and improved solutions that can provide enhanced and reliable performance in subsea pipeline monitoring. Today, companies for subsea pipe monitoring use solutions that are expensive, complicated, unreliable and with limitations in data transfer between the subsea and the host location. The most common way of monitoring an underwater pipeline is by using ROV (Remote Operated Vehicles) [1]. In this solution, an ROV goes from sensor to sensor and forwards data to a remote host via the control umbilical back to the ROV vessel. With a system like this communication cannot be transmitted to remote locations/hosts. If real-time communication is not necessary, this solution is used as a reliable way to collect data with the cost of ROV vessels as the main disadvantage. Another possible solution is to use wire to connect seabed sensors and a surface node, but this is not practical, it is expensive and complicated to deploy and maintain such systems.

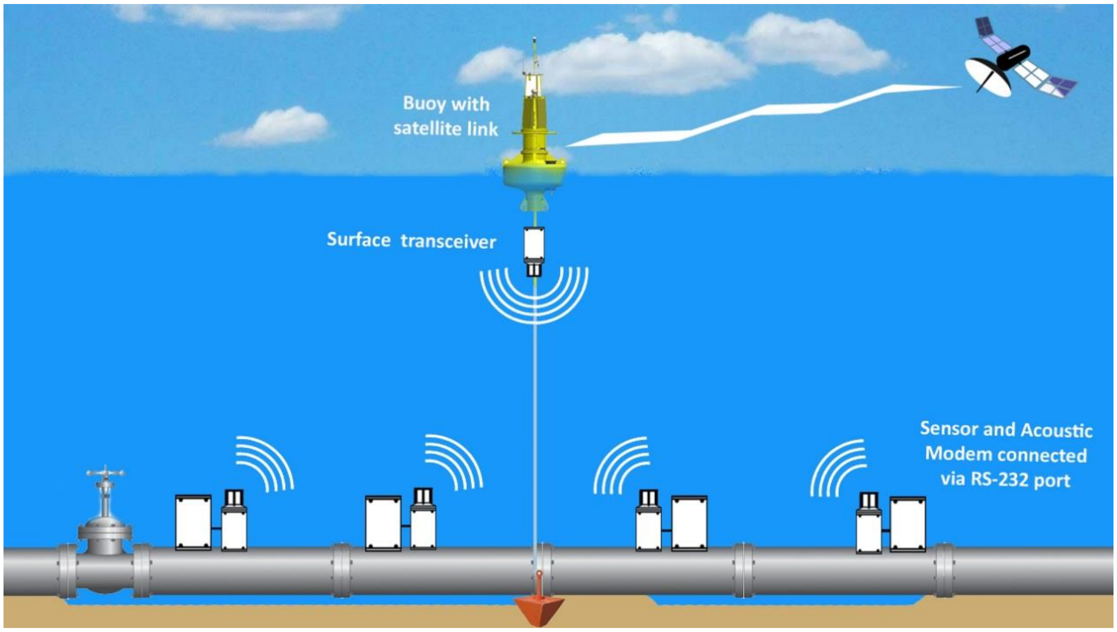


Figure 1.1: Illustration of seabed to a remote host network

The main task in this thesis is to design a wireless network between sensors on the seabed and a remote host at any location, as shown in Figure 1.1. This specific task can be divided into two parts, because of significant difference in the underwater and terrestrial environment. The first part is underwater wireless communication between the seabed and the surface, and the second part is wireless communication from the surface to a remote host. In the first part of the task, sensors on the seabed need to collect data about pressure and Pipeline Inspection Gauge (PIG) [2] passing through the pipes. The collected data are forwarded from sensors to a surface node via a wireless link. The second part of the task is further forwarding of data from the surface node to a remote host via available wireless technology.

1.1. Objective

The thesis will provide architecture design of the system, recommend equipment, and recommend and design a protocol specially tailored to meet the needs of the system. Because of the specific task, where mistakes and malfunction are not tolerated, all technology needs to have perfect track records. All equipment recommended for the system will be COTS (Commercial off-the-shelf) products. The best available COTS technology will be combined in order to achieve the desired requirements of the system. The only problem is small reprogrammability possibilities of COTS products. This system cannot be perfectly customized to the problem; this is due to the proprietary technology of COTS equipment.

1.2. System requirements

The solution needs to satisfy the following requirements:

- Reliability: The system needs to be reliable under all conditions; this is the most important requirement.
- Robust build: As the underwater environment is very harsh, the equipment should be able to withstand the harshest conditions.
- Easy deployment: Installation at the site should be easy (plug and play).

- Back-Up: The system needs to pose some backup strategy for contingency.
- Energy efficiency: The system should be able to work with limited energy.
- Maritime rules: The system needs to be in line with maritime rules.

1.3. Related Work

Underwater WSN systems used for observing, monitoring and surveillance of oceans and structures in them have already been suggested, and a variety of different technologies are used as a possible solution for this problem.

Possible sensor network architectures for pipeline monitoring have been proposed in [3]. This article proposes network architectures that use wire, acoustic link, RF link, integrated wired/RF and wired/acoustic for communication. In this paper, possible advantages and disadvantages of the proposed solutions have been discussed.

Fault-tolerant acoustic sensors architecture has been suggested in [4]. This paper analyses types of faults in line architectures and provide solutions for achieving a fault-tolerant system.

Design and testing of an underwater acoustic sensor network have been presented in [5]. This paper gives us a layer structure design network that can be used as the groundwork for the development of other systems.

In the paper [6] a system for maritime first-alert surveillance has been presented. This system is designed to detect the passage of a maritime vessel and to send information about it to a remote location. The system uses an underwater sensor network and a surface buoy with a satellite link for forwarding information.

A near real-time deep ocean observatory has been presented in [7]. This observatory uses subsea nodes to collect data from the seabed, and via acoustic modems and geostationary satellite, the system transfers data to a remote location for further data analyses.

1.4. Thesis Outline

Chapter 2 – Underwater WSN

Chapter 2 gives a background overview of key concepts of Wireless Sensors Network. The basics of the acoustic channel and Media Access protocols are explained in this chapter.

Chapter 3 – **Surface network**

Chapter 3 gives an overview of satellite and radio frequency communication.

Chapter 4 – **Simulation tools**

Relevant simulation tools are presented in this chapter.

Chapter 5 – The design of system

Design and implementation details of the developed system are presented in this chapter.

Chapter 6 – Simulation and analysis

Simulation results of the system and analysis of these results are given in this chapter.

Chapter 7 – Conclusion

Chapter 7 gives conclusions and ideas for future works.

2. Underwater WSN

In today's world, where data and information are crucial for research and development, Wireless Sensor Network, or short WSN, has found its purpose in almost each branch of industry. They can be used for military purposes, ocean monitoring, smart house application, and so on.

2.1. WSN basic

The usage of WSN is based on using consumable nodes that can sense, store and send information using the wireless link. Requirements like routing protocols, the reliability of networks, power efficiency, data flow and hardware restriction, define specific conditions in WSN architecture development and their application. To develop WSN, it is necessary to combine multiple fields. It is important to make cooperation between communication technique, sensors platform and the application part that is intended for end users. The main use of nodes in WSN is collecting information from the environment and transferring to the remote host for further analyses. To achieve that, three main operations are combined in a single node (Figure 2.1). They use sensors system to collect data, CPU and storage system to process and store that before sending and a communication system to transfer data from the storage to a remote host. Also, every node has to have some power supply and, if it is possible, the power generator to recharge the power unit. If it is necessary, the node can also have additional interfaces, like Location system.

For data collecting from the environment, we can use a single sensor node or multiple nodes that create a sensor field. The sensor field is a collection of sensor nodes in one area with a small distance between them. In the case when the sensor field is deployed, the area can be wholly or partially covered, depending on the density of sensor nodes.

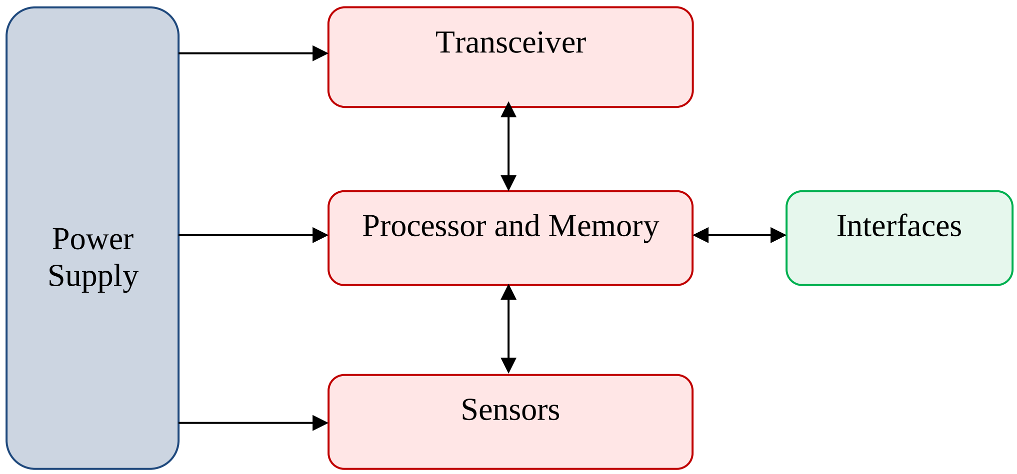


Figure 2.1: Architecture of node in WSN

Data collected with sensor nodes are transmitted to sink nodes with single-hop or multi-hop path (Figure 2.2). Sink nodes act as a gateway between the sensor field and other parts of the network or directly to the end user. The sink provides two-way communication between, for example, the end user and sensor nodes that are using the sink. Two-way communication represents sending the collected data from sensor nodes to the end user, and sending configuration commands from the end user to sensor nodes. Communication of the sink with the end users can be achieved with any available communication infrastructure which satisfies the needs of the WSN network.

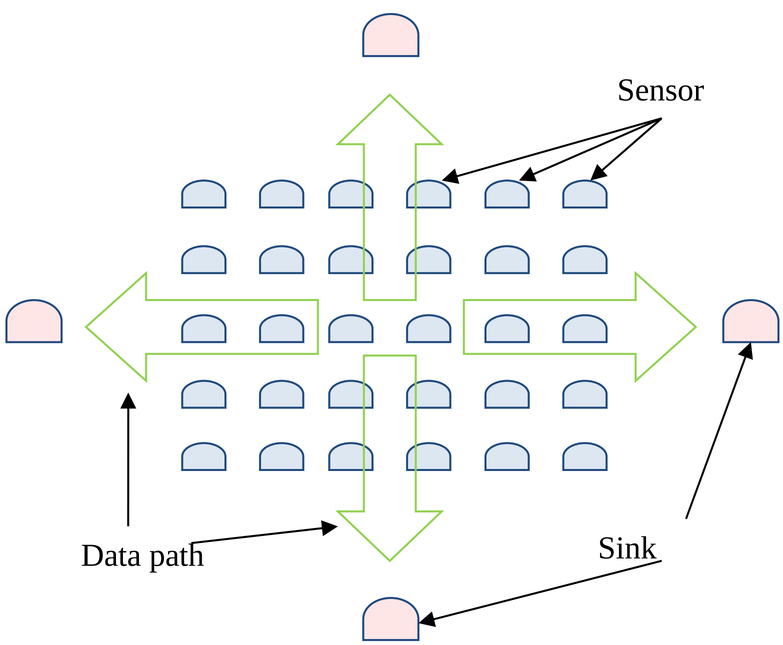


Figure 2.2: Communication direction in WSN

WSN can be divided by environment:

- Terrestrial WSN: Group of nodes that are deployed in the terrestrial environment and use Radio Frequency (RF) channel for communication.
- Underground WSN: Group of nodes deployed in the underground environment with the purpose of sensing environment conditions.
- Underwater WSN: Group of nodes and/or ROV deployed in the underwater environment.

UWSN has enormous potential for exploring and monitoring mostly unexplored ocean depths. They can be used in underwater military surveillance, offshore exploration, tsunami warnings and pollution monitoring. To make all these possible, some sort of wireless communication between nodes is necessary. However, in the underwater environment, that is not a simple task.

UWSN transmission types:

- Optical
- RF
- Acoustic

Water itself is not a conductor, but it can be, in combination with dissolved minerals (for example salt). According to [8], average seawater conductivity is 4 S/m, but with the increase of salinity and temperature, conductivity can rise to 8 S/m. With water conductivity increasing, radio signal attenuation is also increasing.

Radio signals have some good characteristics in the underwater environment. They can easily cross borders between air and water, they are resistant to acoustic noise, and they have high bandwidth. However, because of high attenuation of radio signals in sea water, transmission distance is very small. To accomplish long distance communication with radio signals of Very Low Frequency (3–30 kHz) and Extremely Low Frequency (3-300Hz) must be used. However, these frequencies have a very low bandwidth, and they require high transmission power and quite large antennae. Although the radio signal in the underwater environment has some advantages, a limitation with transmission distance restricts using it only for short-range applications.

Optical transmission in the underwater environment does not suffer from high attenuation like radio signals, and they can achieve very high bandwidth. However, to achieve long distance transmission, they need good alignment of nodes, a line of sight and clear water. If the water is not clear, scattering significantly affects the transmission range.

Acoustic is a proven technology in long range underwater communication. This way of transmission can transfer data onto several kilometers long distance, but with limited bandwidth and high propagation. Due to the usage of the acoustical carrier instead of the electromagnetic one, the propagation speed of the signal is 1,500m/s, and the available bandwidth is in the range of dozen kHz.

Underwater Acoustic WSN Challenges:

- High propagation: compared to electromagnetic signals that propagate with light speed, acoustic signal propagation is much slower (average 1,500 m/s).
- Variation of signal velocity: Speed of the signal in the underwater environment can vary from 1,450 m/s to 1,550 m/s [9]. This is due to the changes in pressure, temperature, and salinity of the water.
- Available bandwidth: Compared to RF or Optic, it is quite small. The available bandwidth is adequate only for small data transfer.
- Battery power: In the underwater environment, it is hard to replace batteries, and also batteries recharging possibilities are limited. It is very hard or impossible to use solar energy, wind energy and wave energy to recharge batteries.
- Time synchronization: Due to high propagation and variation of signal velocity, it is very hard to achieve time synchronization.
- Service life: Corrosion and equipment failure is very likely to happen in such environment.
- High bit error: This is because of harsh underwater conditions.
- Temporary loss of connectivity: This can happen due to shadow zones.

Architecture

Communication topology for underwater WSN can be divided using spatial coverage and movement ability of nodes. According to [10], standard Underwater WSN topology can be two-dimensional and three-dimensional.

Two-dimensional topology consists of stationary nodes. In two-dimensional architecture, all sensing nodes are anchored on the seabed and communicate with the sink node using vertical or horizontal links. If a sink node is deployed on the seabed as well, communication between nodes and sink nodes will be with a horizontal link. In this case the seabed sink will use the vertical link to forward data to the surface gateway. Also, in some architecture solutions, the sink can be deployed on a surface buoy or ship. In this case anchored nodes use the vertical link to forward data.

In three-dimensional topology, nodes can be mobile or stationary. Stationary three-dimensional topology is similar to two-dimensional topology with one main difference - nodes in the network are not on the same depth. Mobile three-dimensional topology consists of stationary and mobile nodes. This architecture typically consists of a vast number of stationary nodes and a few ROV mobile nodes. The biggest problem in this architecture is routing protocol.

2.2. Basics of the Acoustic Channel

Underwater acoustic channel as a wireless medium is one of the most complicated channels for data transfer. As stated in [8], it is easier to achieve interplanetary communication than long range underwater communication. Underwater acoustic communication is highly affected by several problems, such as variable and low velocity of the acoustic signal, noise, multipath and Doppler spread.

2.2.1. Multipath

In underwater medium multipath mostly depends on two factors, sound velocity variation and link configuration. Link configuration parameters such as the depth of the ocean, range and direction of signal affect greatly the multipath formation. In shallow waters, multipath is more evident than in deep waters, as a result of reflection of the signal on the seabed and the surface, as shown in Figure 2.3. Beside surface and seabed, the signal can also reflect on an object in the water, for example, fish, plankton and water bubbles. In shallow waters the signal will bounce more often than in deep waters. Repeated bouncing will increase inter-symbol interference (ISI) and cause degradation of the signal quality. In addition to multiple reflection signals that arrive at a different time, the receiver can also receive multiple direct signals at different times. This occurs due to the variation of sound velocity. In its way from the transmitter to the receiver, the signal can pass regions of higher or lower propagation speed. This will bend the signal, and it will arrive at different time. The signal that is bent can travel further than the reflected signal; this is due to the absence of reflection loss.

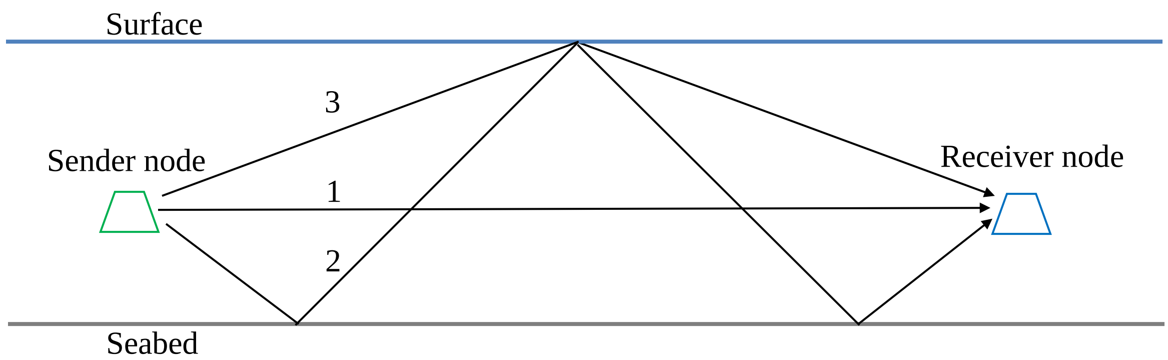


Figure 2.3: Signal reflection in the water. Signal (1) is the direct path of the signal, signal (2) is a reflection on seabed and surface, signal (3) is a reflection on the surface only

2.2.2. Noise

Noise can be a huge problem in acoustic communication, and it is very dependent on the surrounding. In underwater acoustic systems, there are many causes of noise that interfere signal, and they can be divided into three groups:

- Ambient noise: It can be caused by nature or it can be human-made. Nature noise can be standard and come from marine life, waves and wind, or it can be from unique events like underwater volcano eruptions or ice cracking. Human-made noise typically comes from ships or oil rigs.
- Acoustic system noise: It is caused by other acoustic systems.
- Self-noise: It is caused by the system itself.

2.2.3. Doppler

The Doppler-effect [11] is a shift in wave frequency observed by a receiver that is moving relatively to the source of the wave. To produce Doppler-effect source, receiver, sender or both need to be in motion. This effect leads to distortion of the signal; this is especially expressed in acoustic communication because of the low propagation speed of sound. According to [12], Doppler-effect is proportional to the ratio $a = v/c$, where v is the relative speed of node and c the speed of the wave. Using this formula, it is clear that Doppler-effect is more expressed in acoustic communication than in the communication that uses electromagnetic waves. In satellite communication, Doppler-effect can be a problem in LEO satellite systems, where the velocity of satellites is up to 24,000 km/h. Unlike LEO satellite systems, in the underwater acoustic system mobile nodes (ROVs, submarines) move relatively slowly but because of the low velocity of sound that is enough for high magnitude Doppler-effect.

2.2.4. Velocity and variability of propagation

Fundamental equation for the velocity of the acoustic wave was given by Isaac Newton. Newton showed that velocity of the acoustic wave in any medium can be given by the equation:

$$\mathrm{v} = \sqrt{\frac{\mathrm{E}}{\rho}} \tag{2.1}$$

where E (the elasticity of the medium) is the ratio between increasing pressure and decreasing volume, and ρ (the density of the medium) is a mass of medium per unit volume. With this formula, the accurate velocity of the acoustic wave cannot be obtained because the effect of temperature on velocity has been neglected.

The velocity of the acoustic wave in water is variable; this particularly refers to salty waters. Three main factors affect the velocity of the acoustic signal in seawater: temperature, salinity and pressure. The temperature of oceans depends on several factors, such as depth, currents, solar heating and surface mixing. In the surface layer of oceans, temperature varies drastically compared to the ocean depth. Solar energy heats only a few meters of ocean surface layer, but in combination with surface mixing (winds and waves), that can be extended to a few dozen meters. Below the mixed surface layer temperature drops with depth increase. This usually continues until 1,000 meters, after which the temperature becomes almost constant. Salinity represents the amount of salt in water; it is typically measured as the amount of dissolved salts per one kilogram of water. The average salinity of oceans is 34.9 g/kg [13], but this amount can fluctuate greatly. Near coasts and river mouths salinity is lower due to a large amount of fresh water that empties into the ocean. Also, in closed seas, such as the Mediterranean Sea and the Dead Sea, salinity is much higher.

Pressure increases linearly with depth increase. With temperature, salinity and pressure increasing, the velocity of the acoustic wave also increases.

The highly accurate equation for calculating the velocity of the acoustic wave in sea water is given by [14]:

$$\begin{aligned} v = {} & 1448.96 + 4.591\mathrm{T} - 0.05304T^2 + 2.374 \times 10^{-4}T^3 \\ & + 1.340(S - 35) + 0.0163D + 1.675 \times 10^{-7}D^2 \\ & - 0.01025T(S - 35) - 7.193 \times 10^{-13}D^3 \end{aligned} \tag{2.2}$$

where T represents temperature in Celsius, S is salinity in parts per thousand and D represents the depth of water in meters. This equation can be used for calculating the velocity of the acoustic wave in sea water with the temperature range from 2 to 30 Celsius, salinity range from 25 to 40 parts per thousand and the depth range from 0 to 8,000 meters.

2.3. Media Access Control

MAC (Media Access Control) is the sub-layer of Data Link layer in OSI model (Open Systems Interconnection model). The primary task of MAC is to regulate access to a physical medium at any point in time. In addition to medium access regulation, MAC is also engaged with energy efficiency, throughput, and latency. MAC protocols can be grouped into three categories:

- Conflict Free MAC protocols
- Contention-Based MAC protocols
- Hybrid MAC protocols

Conflict Free MAC protocols are designed to avoid collision by assigning resources to each node exclusively. These resources can be frequency intervals, time slots or codes, depending on the applied technology. Basic conflict free protocols are FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access) (Figure 2.4).

Contention-Based MAC protocols, unlike the previous one, avoid exclusively assigning resources to nodes and allow them to compete for them. In this case, collision is highly possible, and the main task of the protocol is to deal with it. Basic conflict free protocols are Aloha, Slotted Aloha, and CSMA (Carrier Sense Multiple Access).

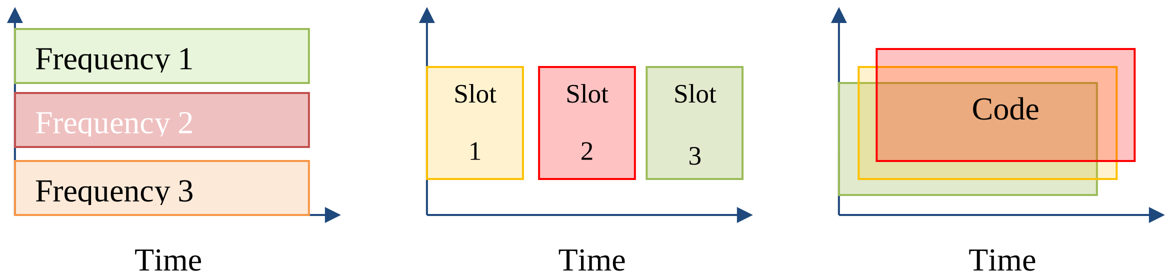


Figure 2.4: Concept of FDMA, TDMA, and CDMA protocols

Hybrid protocols are a combination of the previously mentioned types of MAC protocols in order to utilize their good qualities.

The design of MAC protocol for most USAN applications is subject to achieving energy efficiency to extend the lifetime of nodes and the whole network. Apart from the energy efficiency, MAC protocol also must provide high reliability of data, low latency transport, scalability and adaptability to changes in size and the number of nodes.

Depending on UASN application, challenges for MAC protocol can be:

- Collision control: If it is known that transmission consumes most energy of the node, MAC protocol most important requirement should be in this case collision avoidance.
- High delay: Protocols that use some of the handshaking techniques are particularly exposed to this problem. Due to high propagation, the delay in acoustic communication performance of MAC protocols can be weak if handshaking technique is in use.
- Hidden terminal: MAC protocols that use carrier sense technique are highly exposed to this problem.
- Synchronization: Time Synchronization can be a big challenge in UASN. Propagation delay and restriction on energy consumption decrease the accuracy of synchronization. MAC protocol, like TDMA, highly depends on the accurate time synchronization.
- Topology: Network topology must be taken into consideration during MAC protocol design. Sparse or dense node distribution can affect very differently the performance of the protocol.

2.3.1. ALOHA

First MAC protocol ALOHA was developed in Hawaii University by Professor Norman Abramson [15]. ALOHA was a part of innovation network system ALOHAnet (Additive Links On-line Hawaii Area Network), one of the first wireless packet of data networks. The goal of this network was to connect users on sparse Hawaiians Islands with the central server.

Pure ALOHA

ALOHA is Contention-Based random access MAC protocol with the simplest medium access method. ALOHA works on the principle that if a node has something to send, it sends it immediately. Pure ALOHA in the original design does not provide any strategy for collision avoidance, and the packet loss can easily occur especially in high throughput and dense networks, as shown in Figure 2.5. ALOHA can be a good solution for networks with very low probability of collision and, in that case, it can provide small delay and energy efficiency.

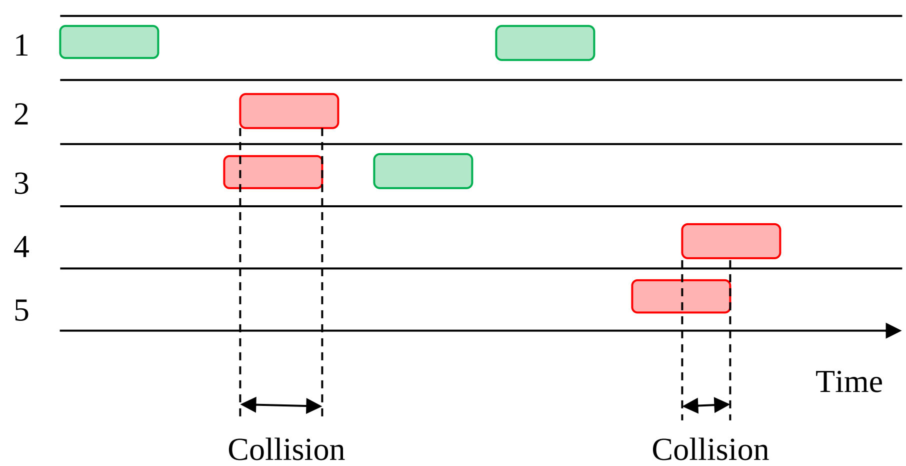


Figure 2.5: Collision example in ALOHA protocol

Slotted ALOHA

Slotted ALOHA is an improvement of the original ALOHA protocol. In Slotted ALOHA, time is divided into discrete time slots, and when nodes have data to send, they need to wait for next slot, as shown in Figure 2.6. This little improvement significantly increases data throughput [16], but now protocol becomes more complicated, some form of time synchronization is required. Time synchronization of nodes needs to be as accurate as possible. Inaccurate time synchronization can contribute to increasing number of collisions and consequently it results in the reduction of data throughput of the network. Collision probability is growing in this case because time slots in different nodes can start in different time instance and nodes can start sending in the middle of another transmission.

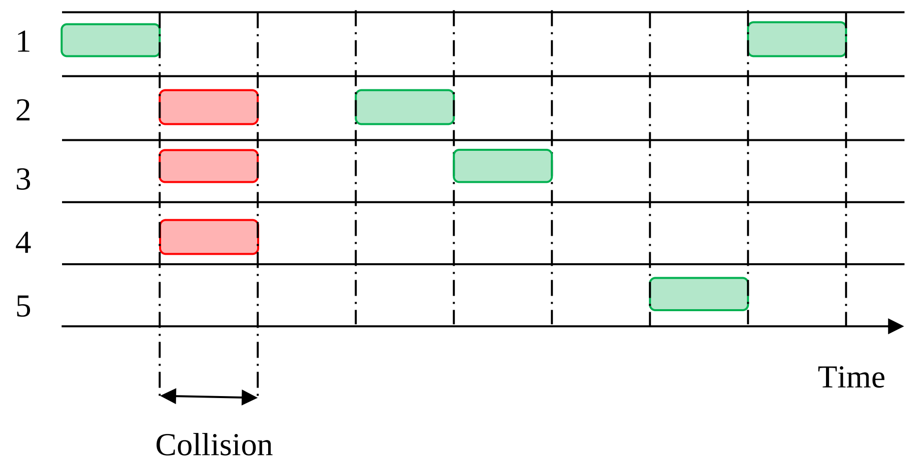


Figure 2.6: Slotted ALOHA with perfect time synchronization

Enhanced ALOHA

In the original design, ALOHA does not provide any strategy for collision avoidance and detection, but with some improvement, this can be achieved.

ALOHA can be enhanced with ARQ (Automatic Repeat reQuest) and detected when a collision occurs. In this design, the destination node will send back ACK packet after a successful reception of data. The sender node will wait for ACK and will not send new data packet until it receives ACK. If the destination node does not receive data or ACK packet is lost in transmitting back to the sender, the sender will wait until ACK timeout and back-off time, and then retransmit the packet (Figure 2.7). Back-off scheme is a random time in a specified time interval and helps to avoid a new collision.

To avoid collision ALOHA can be improved with carrier sense capabilities. In this solution (ALOHA/CS or CSMA ALOHA [5]) nodes before sending the packets first sense the medium; time of sensing is chosen randomly and it is much shorter than the standard packet transmission time. After sensing if the channel is free, the node can start sending, and if the medium is occupied, the node will wait a random time before retrying. This solution improves collision avoidance but does not guarantee collision-free transmission. It is possible that two nodes sense medium at the same time, conclude that medium is free and then start sending data at same time. This problem especially occurs in networks with high propagation delay.

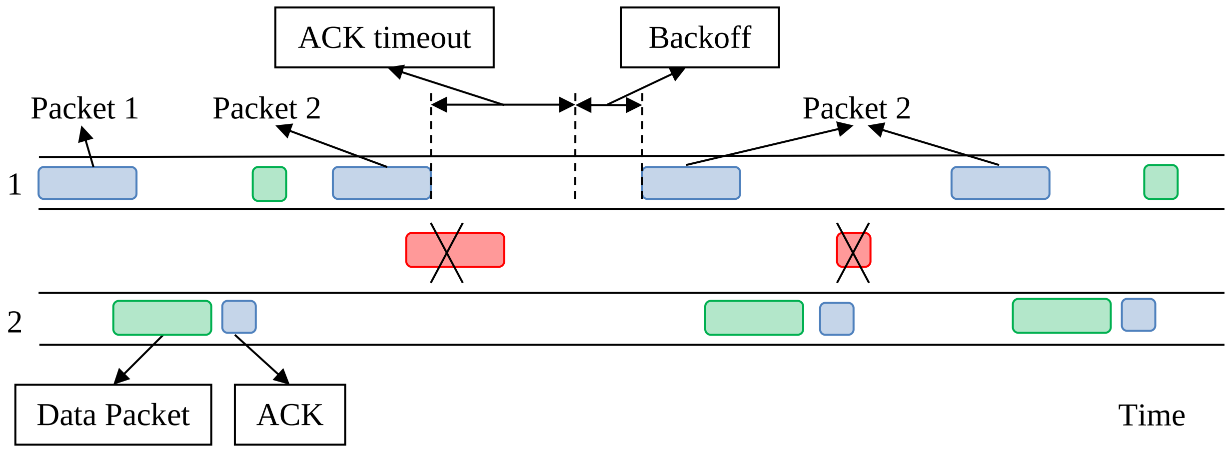


Figure 2.7: Illustration of collision detection in ALOHA-ACK

2.3.2. CSMA

Carrier Sense Multiple Access or short CSMA [17] is MAC protocol that uses carrier sense as a strategy to avoid the collision. In this protocol, each node before transmitting data first checks the medium and verifies that it is free. If the node concludes that medium is free, the packet transmission can start, but if a node finds the medium busy, it will wait a random time before trying again. Like ALOHA-CS, the basic CSMA does not guarantee complete collision avoidance. There are four access modes for CSMA protocol:

- Non-persistent: In this CSMA access mode, nodes first sense the medium before transmitting. If the medium is free, the node can send a packet, but if it is not, the node will back-off random time. This back-off time grows exponentially. After the random time passes, the node will start the whole procedure from the beginning. This approach provides good collision avoidance but with a long delay at the start.
- 1-persistent: Like the previous access method, 1-persistent method senses the medium and if the medium is free, transmission can start right away. However, if the medium is busy, the algorithm will wait until it is free (constantly listening to the medium) and then send

the packet. If a collision occurs during transmission, the node will wait for a random time and start the procedure from the beginning.

- P-persistent: This method is a balanced approach between previous methods. P-persistence does not send immediately if the medium is free, instead, the method uses probability *p* to decide. If the medium is busy, the algorithm will continuously listen to the medium and after the medium is free, then transmit with *p* probability.
- O-persistent: In this method, the main node will decide the order of transmission for each node. When the medium goes to the idle state, the first node in the list will start to transmit the packet immediately, and others will wait.

CSMA/CA

Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) [18] is the enhanced CSMA MAC protocol. Protocol uses the same carrier sense strategy as CSMA but also tries to tackle the hidden terminal problem [19]. For this problem, CSMA/CA uses Request to Send - Clear to Send (RTS/CTS) technique. As shown in Figure 2.8, if the node has data to send and the channel is free, the node will first send RTS packet and if CTS packet is sent back from the destination node, data can be transmitted.

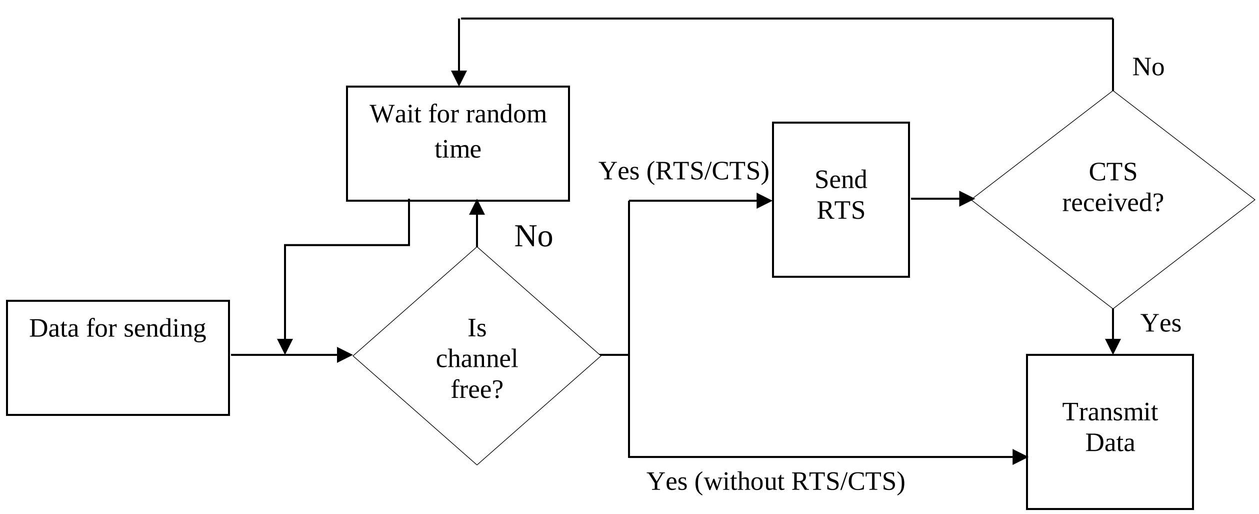


Figure 2.8: CSMA/CA algorithm with RTS/CTS and without

The Hidden terminal problem occurs in three nodes network configuration, as shown in Figure 2.9. In this configuration node B is in the range of A and C, but A is not in the transmission range of C and vice versa. In this situation, node C cannot sense any transmission between nodes A and B, and C can easily interfere with ongoing transmission between these two nodes. To overcome this problem several solutions are proposed, and two most popular are RTS/CTS packet and increasing carrier sensing range.

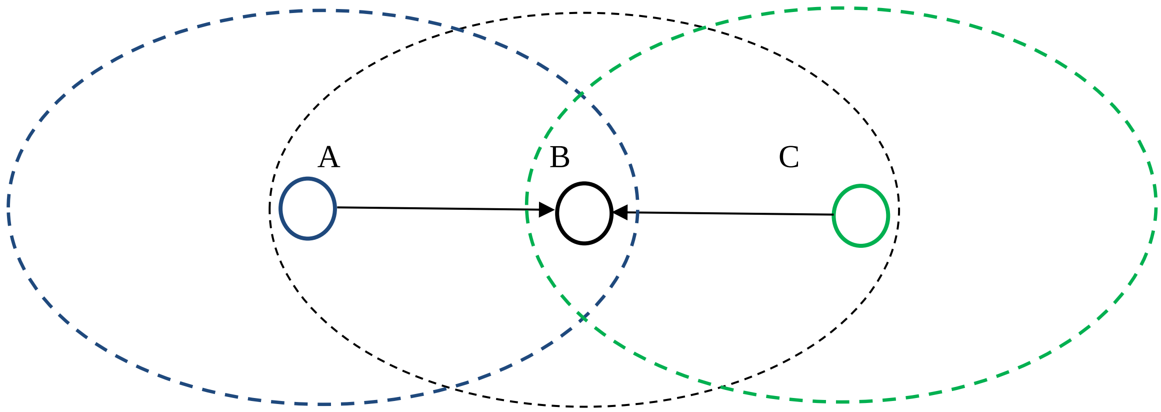


Figure 2.9: Hidden terminal problem

2.3.3. TDMA

Time Division Multiple Access (TDMA) [20] is a medium access protocol which allows multiple nodes to use the same frequency by splitting time into frames. Time is divided into frames, and each node receives one fixed time slot in the frame, as shown in Figure 2.10. Each node will send data only into their own slots. After slot time is finished, the node will wait for next frame. To avoid crosstalk between two slots, guard time is added after each slot.

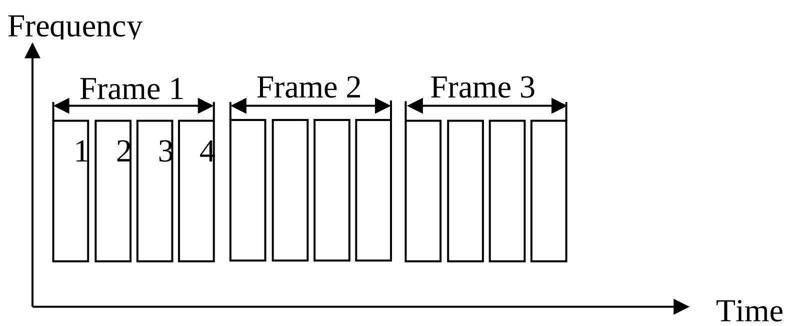


Figure 2.10: Time Division Multiple Access protocol concept

With this technique, every node gains access to completely available bandwidth in a fraction of the time. This technique is suitable for static data transmission, it equally divides available network resource and guarantees collision-free transmission. The drawbacks of this protocol are poor utilization of resources and the need for time synchronization. The use of resources is poor in event-driven and burst systems; there is no option in standard TDMA to redistribute slots to other nodes and because of that idle nodes waste available resources. Also, the guard time between every slot reduces available time for transmission, this especially present in systems with the long propagation time of the signal.

3. Surface Network

Surface communication between the buoy and the remote location is not the main task. There are many solutions on the market that can be used. This chapter gives a brief review of technology for surface data transfer and is divided into two parts: satellite communication and terrestrial communication.

The position of oil pipeline can be far from the shore, and that can be a problem for terrestrial communication that needs LOS and has a limited range. Still, terrestrial communication can be an appropriate solution in a situation when the system is deployed near an oil platform or a vessel.

3.1. Satellite communication

Satellite communication network is data transfer system between geographically remote locations. This network represents a combination of nodes, and some of these nodes are satellites.

Satellites use two different frequency ranges for sending and receiving signal, the signal from the satellite to the earth is called downlink, and from the earth to the satellite is uplink. Satellite communication is in GHz frequency range, and most satellites use super high frequency (SHF). With increasing frequency, available bandwidth is also increasing but also signal attenuation is becoming more pronounced. In Table 3.1 frequency bands and their applications in satellite communication have been shown.

Table 3.1: Satellite communication frequency bands and their applications [21]

Frequency range in GHz	Bands	Applications
1.0 - 2.0	L	Mobile satellite services (MSS): LEO, MEO, Iridium, Inmarsat, GPS
2.0 - 4.0	S	MSS
4.0 - 8.0	C	Inmarsat between stations and satellite, INTELSAT
8.0 - 12.0	X	Military and governments
12.0 - 18.0	Ku	INTELSAT, direct broadcast
18.0 – 24.0	K	Broadcast satellite service(BSS), Fixed satellite service (FSS)
24.0 - 40.0	Ka	Commercial MSS, crosslinks, satellite-to-gateway links of Iridium, INTELSAT IA-8

Based on the distance from the earth, satellites are grouped into three categories:

- Geostationary Earth Orbit (GEO)
- Medium Earth Orbit (MEO)
- Low Earth Orbit (LEO)

These satellite orbits are separated by Lower Van Allen belt and Upper Van Allen belt, as shown in Figure 3.1. Van Allen belt [22] is a zone that contains energetically charged particles, and radiation from this zone affects communication and electronic circuitry.

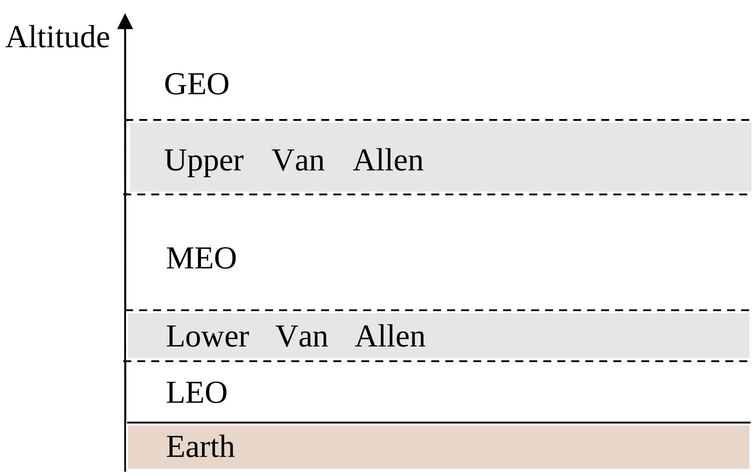


Figure 3.1: Satellite orbits and Van Allen belts

3.1.1. GEO

GEO satellites are set at an altitude of 35,786 km from the earth surface. At this altitude, the satellites have the same angular speed as the earth, and they will stay at the same position as the earth rotates. Because of this characteristic, GEO satellites provide a constant line of sight and cover a wide area. To cover the entire earth's surface, only three GEO satellites (satellites are separated by an angle of 120) are enough. GEO satellites are mostly used for weather forecasting, broadcasting of TV and radio signals.

Advantages of GEO satellites:

- Covered area, only three satellites cover the whole Earth.
- GEO satellites do not require tracking terminals; this is due to the fixed position of satellites.
- Doppler shift does not have effect on GEO satellites.
- GEO satellites lifetime is long, compared to other types of satellites.

Disadvantages of GEO satellites:

- The biggest problem with GEO satellites is high latency. Average round trip delay is 240 ms, and that kind of delay is unacceptable in real-time communications.
- The cost of satellite deployment is high; this is due to high altitude.
- The polar region does not have good coverage.
- Communication with GEO satellites requires high power; this is due to the long distance between the satellite and a station on the earth.

3.1.2. MEO

MEO satellites are placed between Lower Van Allen belt and Upper Van Allen belt, at the altitude from 10,000 km to 16,000 km. Because of smaller altitude, MEO satellites have higher angular speed than the earth. The time required for MEO satellite to make the trip around the earth is less than 24 hours, and with that trait line of sight between the satellite and the station on the earth is not constant. MEO satellites are mostly used for the Global Positioning System (GPS).

Advantages of MEO satellites:

- MEO satellites have an acceptable round trip delay. The delay for this type of satellites is less than 70ms.
- MEO satellites require ten satellites to cover the whole Earth. This is worse than GEO satellites but much better than LEO satellites.

Disadvantages of MEO satellites:

- MEO satellites do not have fixed positions, and because of that, tracking terminals are required.
- This type of satellites requires high transmission power.

3.1.3. LEO

LEO satellite orbit location is between 500 and 1,500 km from the earth surface, with a rotation period of 80 to 130 minutes and the velocity of the satellite is from 18,000 to 24,000 km / h. LEO system is usually characterized by the cellular type of access similar to the one used in cellular telephony, footprint on Earth has a diameter of approximately 8,000 km depending on the heights of the satellite. Since LEO satellites are closer to Earth, propagation delay is less than 20ms, which is acceptable for real-time communication, compared to GEO satellites which have delay time of approximately 240ms. LEO system consists of constellation satellites that are organized in a network, with the satellite acting as a switch in that network. Communication is in this system is divided in three ways, as shown in Figure 3.2. The satellites that are closer to one another are connected with inter-satellite links (ISL), the mobile system to communicate with satellite us mobile users link (UML) and satellite can communicate with the earth station (gateway) via a connection gateway link (GWL).

Advantages of LEO satellites:

- The small cost of deployment, it is easier to deploy a satellite in LEO orbit.
- Because of the short distance to Earth surface, Leo satellites have very low propagation delays. Low propagation delay is a critical characteristic, especially in real-time communication.

- Due to a small distance from the earth surface, it is easier for LEO system to receive a signal than for a higher orbit system with the same transmission power. This characteristic allows us to have less complicated terminals.

Disadvantages of LEO satellites:

- Because of low-level orbit position in LEO system, we have a short lifetime of satellite and consequently, bigger costs of the system.
- Due to a small distance from the earth surface, LEO satellite has a smaller footprint than GEO and MEO satellites. This means that we need more satellites to cover the earth surface. For example, it is enough to have three GEO satellites to cover the earth and a few dozens of LEO for the same job (Iridium satellite constellation has 66 satellites [23]).
- Small LOS (Line of the site) duration, due to high-velocity the satellite remains visible from some point on earth for a brief time. Also because of high velocity we have a high influence of Doppler-effect.

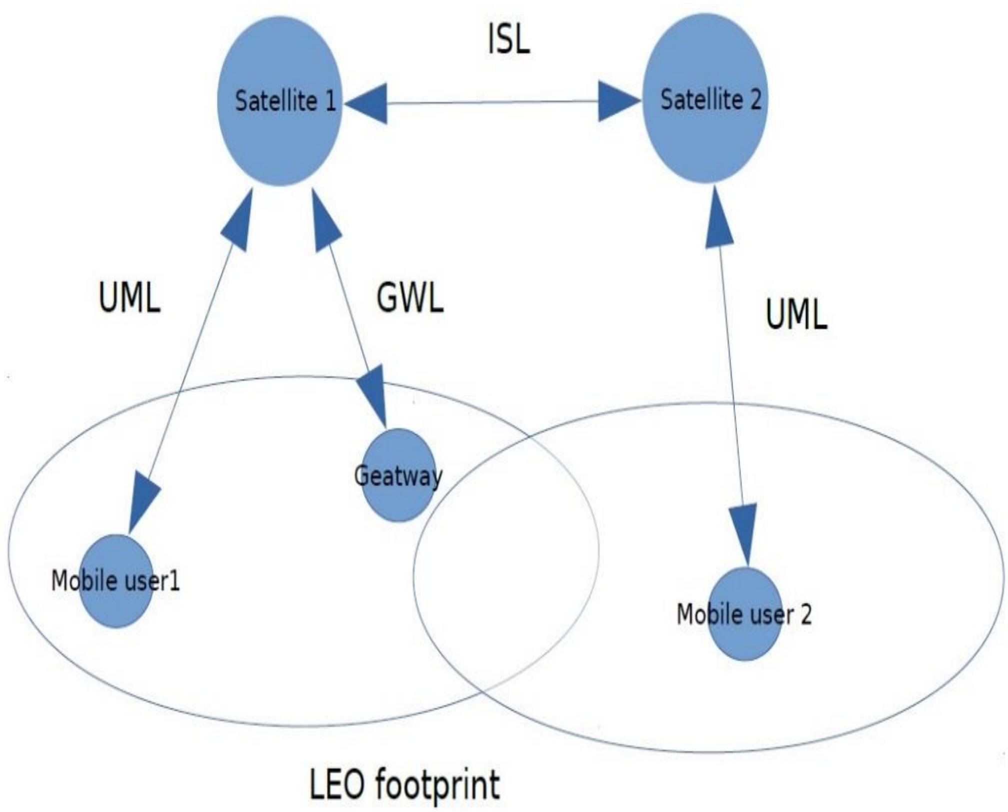


Figure 3.2: concept of LEO satellite system

3.2. Terrestrial Communication

Wireless terrestrial communication systems represent the transmission of data via electromagnetic waves within a local geographical area. Using frequency parameters, the system can be divided into Radio frequency (RF) communication and Microwave communication. RF includes all wireless systems that use frequency less than 1 GHz, and microwave system is between 1 GHz and 300 GHz. To choose the appropriate frequency for a wireless system, several factors need to be considered:

- Frequency license regulations
- Antenna size
- Propagation modes

Electromagnetic spectrum for wireless communication is divided into the one that uses the frequency for free, and the frequency that requires a license from the government. The worldwide unlicensed frequency that is in use for transmission of information is 2.4 and 5.7 GHz. In Europe 433.92 MHz and 869 MHz frequency can be used without a license [24]. Although a license is not required for this frequency, there are some regulations which must be followed. The problem with unlicensed frequency is interference due to a high number of users; this is particularly in densely populated areas.

The size of the antenna could be critical in some applications, and its size is inversely proportional to frequency. Wavelength size can be given by the equation:

$$\lambda = c/f \tag{3.1}$$

where c is the speed of light in m/s and f is the frequency in Hz.

As it shown in Table 3.2, with increasing frequency of a signal, the wavelength of the signal is decreasing, and with that antenna size is also decreasing.

Table 3.2: Frequency bands and propagation modes for Radio and Microwave systems

Frequency	**Wavelength**	**Band**	**Propagation modes**
3 - 30 KHz	100 - 10 km	Very low frequency (VLF)	Ground waves
30 - 300 KHz	10 - 1 km	Low frequency (LF)	
0.3 - 3 MHz	1000 - 100 m	Medium frequency (MF)	
3 - 30 MHz	100 - 10 m	High frequency (HF)	Sky waves
30 - 300 MHz	10 - 1 m	Very high frequency (VHF)	Line of sight
0.3 - 3 GHz	100 - 10 cm	Ultra-high frequency (UHF)	
3 - 30 GHz	10 - 1 cm	Super high frequency (SHF)	
30-300 GHz	10 -1 mm	Extremely high frequency(EHF)	

As shown in Figure 3.3 electromagnetic waves have three methods of propagation:

- Ground wave
- Sky wave
- Lind of sight (LOS)

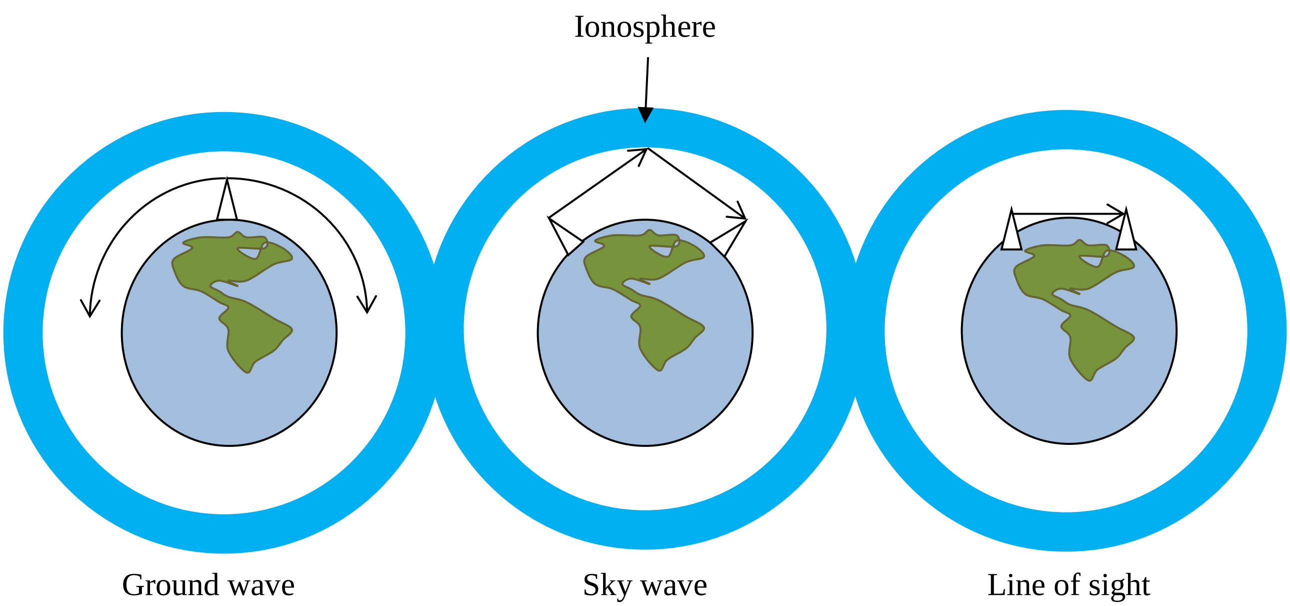


Figure 3.3: Three different methods of propagation of electromagnetic waves in wireless terrestrial systems

The ground wave is an electromagnetic wave that propagates by following the curvature of the earth. Ground waves use VLF, VF and MF radio frequency bands. In theory, everything below 3 MHz frequency is ground waves, but in practical application, only waves below 2 MHz are in use. This is due to high attenuation of waves at higher frequencies. These waves have a long range, but they require big antennae and consume a lot of energy (from a few kW to a few MW of energy).

Sky waves are directed into space, but because of the ionosphere, they are reflected back to the earth. Using this mechanism, sky wave bounces between the ionosphere and the earth, and creates thousands of kilometers long communication channel. The ionosphere is a part of Earth's atmosphere, and according to [25], it extends from 60 km to 1,000 km of altitude. In this segment of the atmosphere the amount of charged particles, generated by sun radiation, is high enough to reflect electromagnetic back to the surface. The ionosphere consists of layers D, E, F and F1. The first two layers D and E are in the range from 60 - 85 km and 85 - 140 km, and they disappear at night. Also, these two layers significantly absorb low-frequency waves. Layers F and F1 are in the range from 140 - 200 km and 200 – 1,000 km. These two layers at night become one layer. Sky waves use HF band, between 3 and 30 MHz, but also MH band higher than 2 MHz can be utilized. These waves also have a long range like ground waves, but they require a smaller antenna and less energy.

LOS wave propagation is based on the visibility between the transmitter and the receiver, with an additional occurrence of surface reflection, atmospheric refraction and diffraction on objects between the transmitter and the receiver. Electromagnetic waves with a frequency above 30 MHz can only propagate with LOS. In addition to the optical line of sight in terrestrial communications, there is also radio line of sight. Radio line of sight propagation occurs due to the bending of microwaves by the atmosphere. Typically, microwaves follow the curvature of the earth, and the range of propagation is therefore longer than the optical one, as shown in Figure 3.4.

The optical line of sight can be given by the equation:

$$d = 3.57\sqrt{h} \tag{3.2}$$

where h is the height of antenna in meters and the result is the distance between the transmitter and the horizon in kilometers. To calculate radio line of sight, an adjustment factor needs to be included in the previous equation:

$$d = 3.57\sqrt{kh} \tag{3.3}$$

where k is an adjustment factor that takes into consideration bending of waves by the atmosphere. In normal conditions, this factor is 1.333.

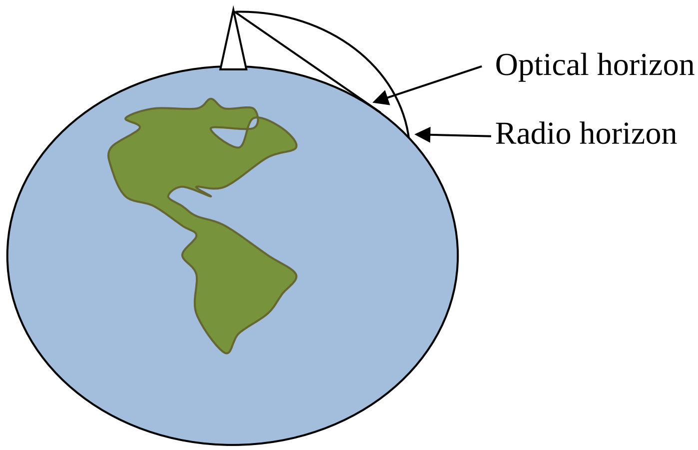


Figure 3.4: Difference between optical and radio line of sight

4. Simulation tools

Real world testing is a reliable and accurate way to understand the behavior of the network, test and verify it, but this is not always an option. Sometimes real testing is too expensive, or dangerous, and in that case, it is handy to use a software tool that can do that cheaply on one host machine. Nowadays there are a large number of software solutions that can perform a network simulation, and to achieve an accurate simulation, only widely used and recognized simulation tools are recommended. Simulation tools can be classified as discrete or continuous [26]. In the continuous model, a system is shown with the state that is changing continuously over time. If the state can change their values in discrete instances of time, in this case, the model is called discrete model. Most network simulators are discrete and available for multiple platforms (Windows, Linux, Solaris, etc.).

4.1. NS2

Network Simulator 2 or short NS2 is a discrete event simulator [27]. NS2 was developed as a part of Virtual Inter-Network Test bed project that was started by Defense Advanced Research Projects Agency. It implements various types of protocol from the application level to lower levels, and it is widely used in simulating of LAN, WAN and ad-hoc networks. It can also generate network traffic, topology and animates the network for better understandings of a user (Figure 4.1).

NS2 was developed in C++ language and OTcl (Object-oriented Tools Command language) [28], but most of the time OTcl will be used. These two languages complement each other to achieve efficacy and speed in the simulation.

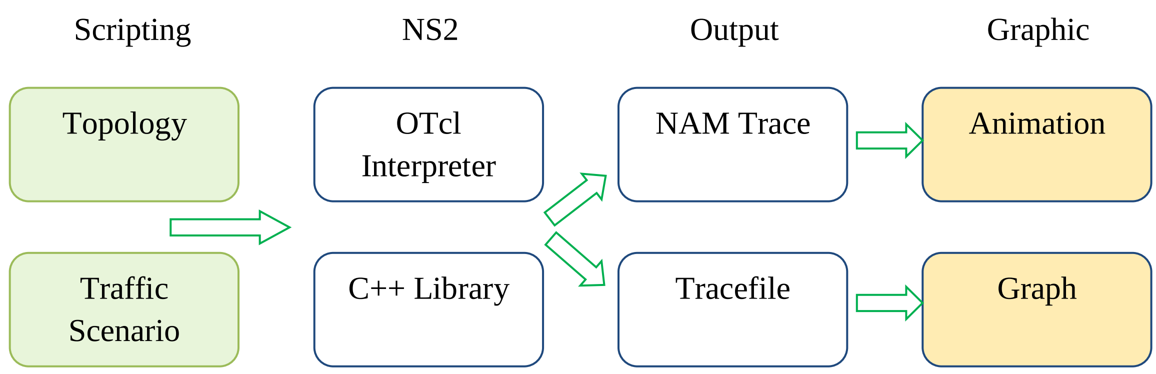


Figure 4.1: Structure of NS2 simulator

The OTcl part in NS2:

- Describe network topology
- Specify protocols and applications
- Spare time on configuration

The C++ part in NS2:

- Increase efficiency of simulation
- Reduce processing time
- Specify details of protocols and their operation

C++ is hard to change and code but it is a very fast language and in NS2 it is used to create the backbone of NS2. On the other hand, it is easy to change and understand, but it is slow to run. OTcl is used to configure simulation.

The simulator consists of three basic network components:

- Node
- Link
- Packet

Node has a function to process a packet using header information (address of the source, protocol type, etc.) and to forward that packet to the following node based on the routing table. They are connected to each other via links, that can be duplex or half-duplex, and for each link the delay is defined due to propagation. In NS2 data structure there is a unit of data that contains of a set of headers from a different protocol, and is routed between the source and the destination in simulated topology.

NS2 also supports additional tools for processing and animation of output files. Detailed analysis of simulation results is based on trace file generated by the simulator. Trace file contains a collection of events, such as packet forwarding, link throughput, etc., sorted in a discrete time of simulation. A tool developed specially for NS2 trace files is Trace Graph. This tool provides the user an extensive range of information that can be used to create graphs in 2D and 3D variation. NAM (Network Animator) [29] is an animation tool that provides tracking of simulation process such as, link state, traffic flows, etc. NAM provides quick verification of scenarios and allows users to control some animation parts (Figure 4.2).

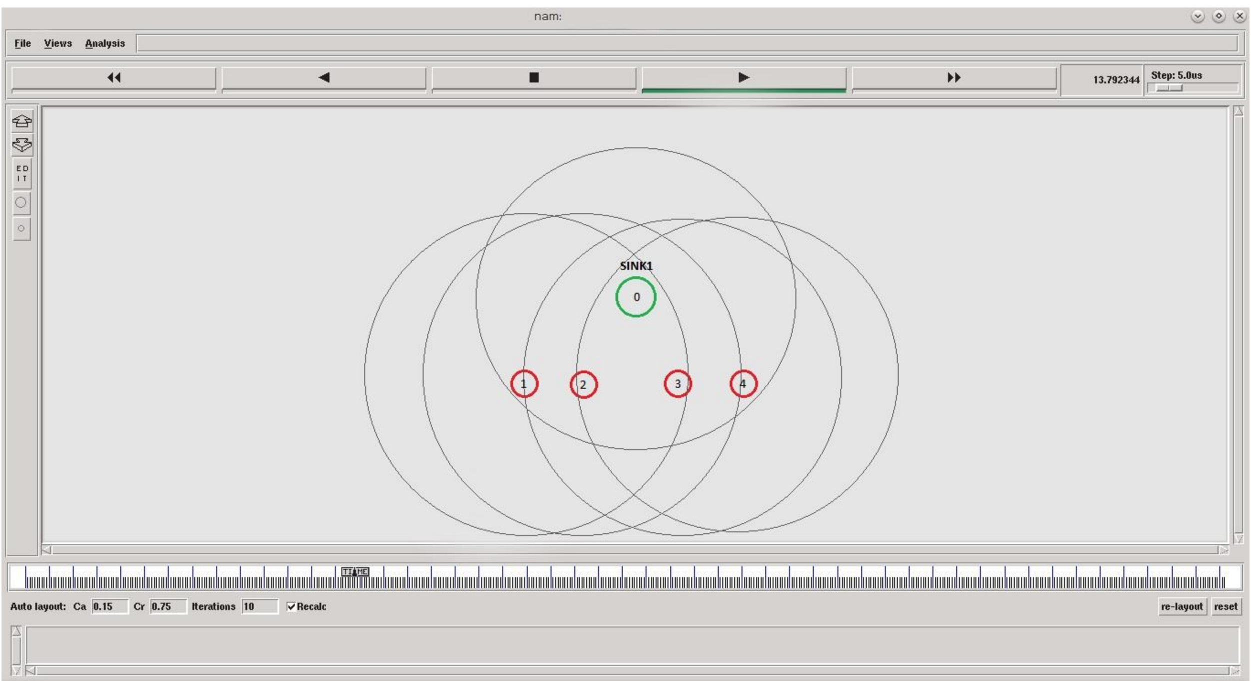


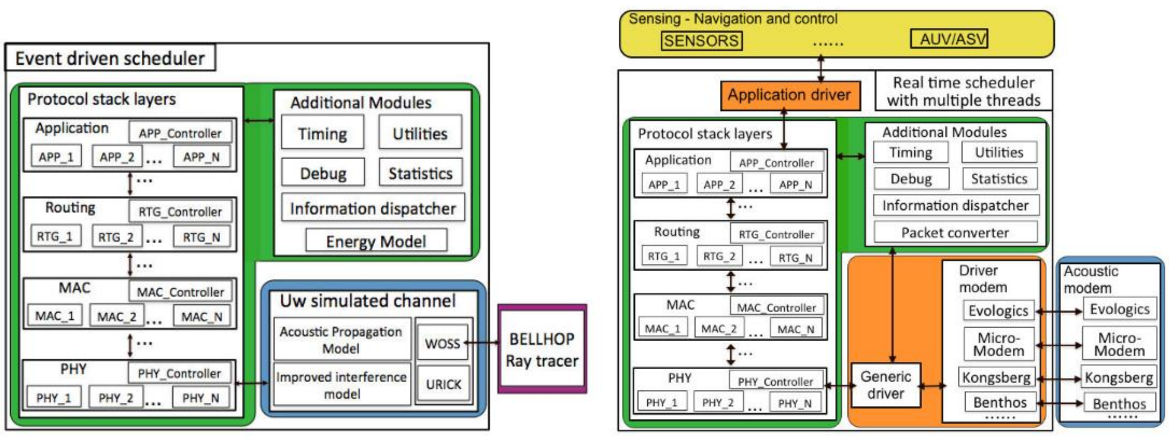
Figure 4.2: Example of NAM animation

4.1.1. NS2 Miracle

Multi-InteRfAce Cross-Layer Extension or short NS-Miracle is a library set created to improve the functionality provided by the NS2 [30]. It provides an efficient solution for cross-layer message handling and supports simultaneous working of multiple modules in a single layer of the protocol stack. MIRACLE implementation with NS2 helps with a simulation of cross-layer networks and enables code reusing due to its modular design.

4.2. Sunset

The Sapienza University Networking framework for underwater Simulation, Emulation and real-life Testing or short SUNSET [31] is an open-source extension of NS2 and NS-Miracle simulators. It has been designed to inspect the performance of UWSN protocols. SUNSET can simulate, emulate and perform field tests, and does not require any special training due to its design similarity with NS2. SUNSET shares the same architecture organization as NS2 and NS-Miracle as shown in Figure 4.3. It allows a cross-layer solution that spreads through multiple layers and also multiple solutions per layer.



(a) SUNSET modules in simulation mode. (b) SUNSET modules in emulation mode.

Figure 4.3: Simulation and Emulation Architecture of SUNSET taken from [31]

SUNSET framework includes several standard protocols of the second and third layer of OSI model:

- Routing protocols: Static Routing, Flooding, Probabilistic Flooding
- MAC protocols: ALOHA, ALOHA-ACK, ALOHA-CS, CSMA, TDMA, Tone-Lohi [32], DACAP [33]

Also, to provide easy implementation, SUNSET implements additional models:

- Core Modules: Timing, Utilities, Debug, Statistics, Information Dispatcher and Energy.
- Emulation Modules: Packet Converter, Real-time scheduler and External device interaction drivers.

4.3. Desert

DEsign, Simulate, Emulate and Realize Test-beds for Underwater network protocols (DESERT Underwater) [34] as well as SUNSET is an open-source extension of NS2 and NS-Miracle simulators. The main difference from SUNSET is in architecture organization; DESERT provides several solutions for each stack layer (Figure 4.4).

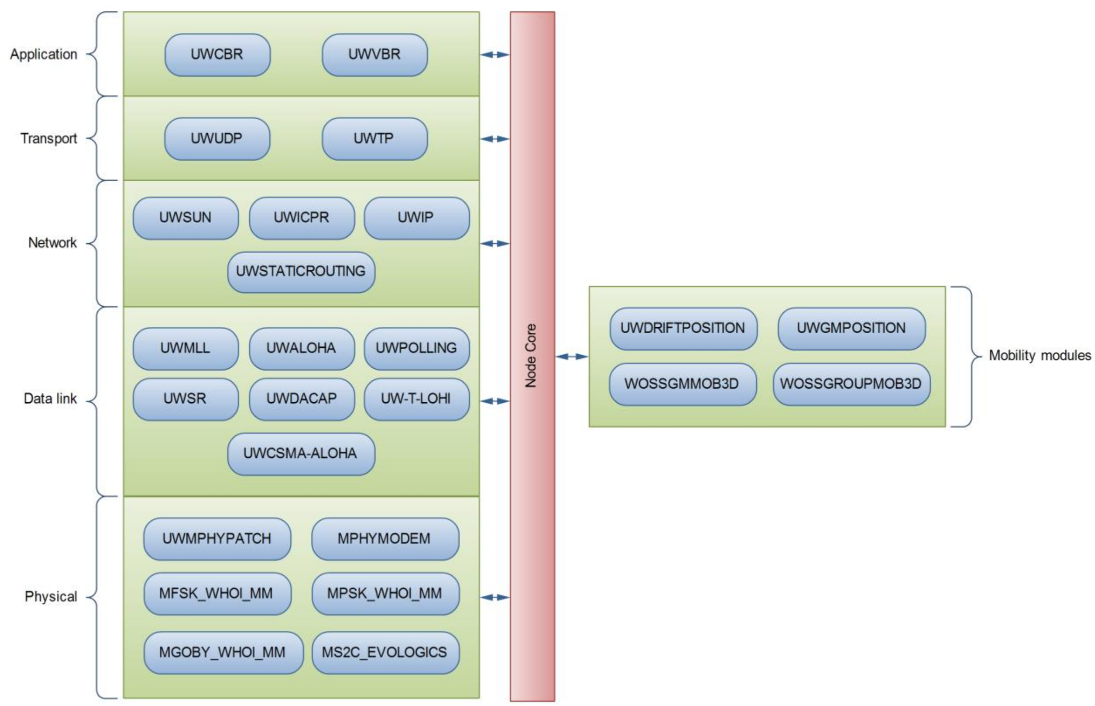


Figure 4.4: DESERT modules organization, taken from [35]

DESERT also includes several MAC and routing protocols:

- MAC: ALOHA, ALOHA-ACK, ALOHA-CS, CSMA, UW-Polling [36], Tone-Lohi, DACAP
- Routing: Static routing, source routing for underwater networks (SUN) [37], ICRP [38]

5. The Design of System

This section will show equipment and technology used in the design with an explanation of advantages and disadvantages. Also, this section will show design and implementation of the system. The section is divided into two parts. The first part is about COTS equipment and solution, and the system design using these elements. The second part will show protocols that will enhance COTS technology for the task presented within this thesis.

5.1. System design with COTS

The main task of the system is to carry out real-time transfer data from seabed sensors to a remote location. The system consists of the components shown in Figure 5.1. Up to six sensors can be deployed in line on the pipeline/seabed, and they will communicate with the surface using acoustic link modem. On the buoy there will be an acoustic modem, the buoy computer, a satellite modem and an RF modem.

5.1.1. Sensors

The system can consist of RAI (Radio Active Isotopes) and pressure logger mounted on an underwater oil pipeline.

In the first phase of pipeline monitoring, RAI sensors will be deployed and the task of these sensors will be to track PIG in the pipeline. RAI sensors will be mounted directly on the pipeline and will detect the PIG (which contains a radioactive isotope) every time it passes nearby with the use of Geiger counter [39]. After detection of a PIG passing, a signal will immediately forward information to the acoustic modem and this information will contain the single character. Up to six RAI sensors together with the acoustic modem can be deployed in depths between 70 and 450 meters; they will form a horizontal line with maximum 400 meters distance between two nodes. The maximum distance between any node on the seabed and sink on the surface will be up to 1,100 meters.

The system can also be used for subsea pressure monitoring. The pressure sensor will be deployed to collect information of pressure in a pipeline after pigging. In this phase, sensors will collect pressure information every second and this data will be forwarded to the acoustic modem immediately after every measurement. In this phase near real-time communication is not possible, delay of the network is bigger than the time between two measurements. Up to three pressure sensors together with the acoustic modem can be deployed in this phase. All distance will be the same like in the first phase, except for the node to the sink distance, and, in this phase, it will be maximum 600 meters.

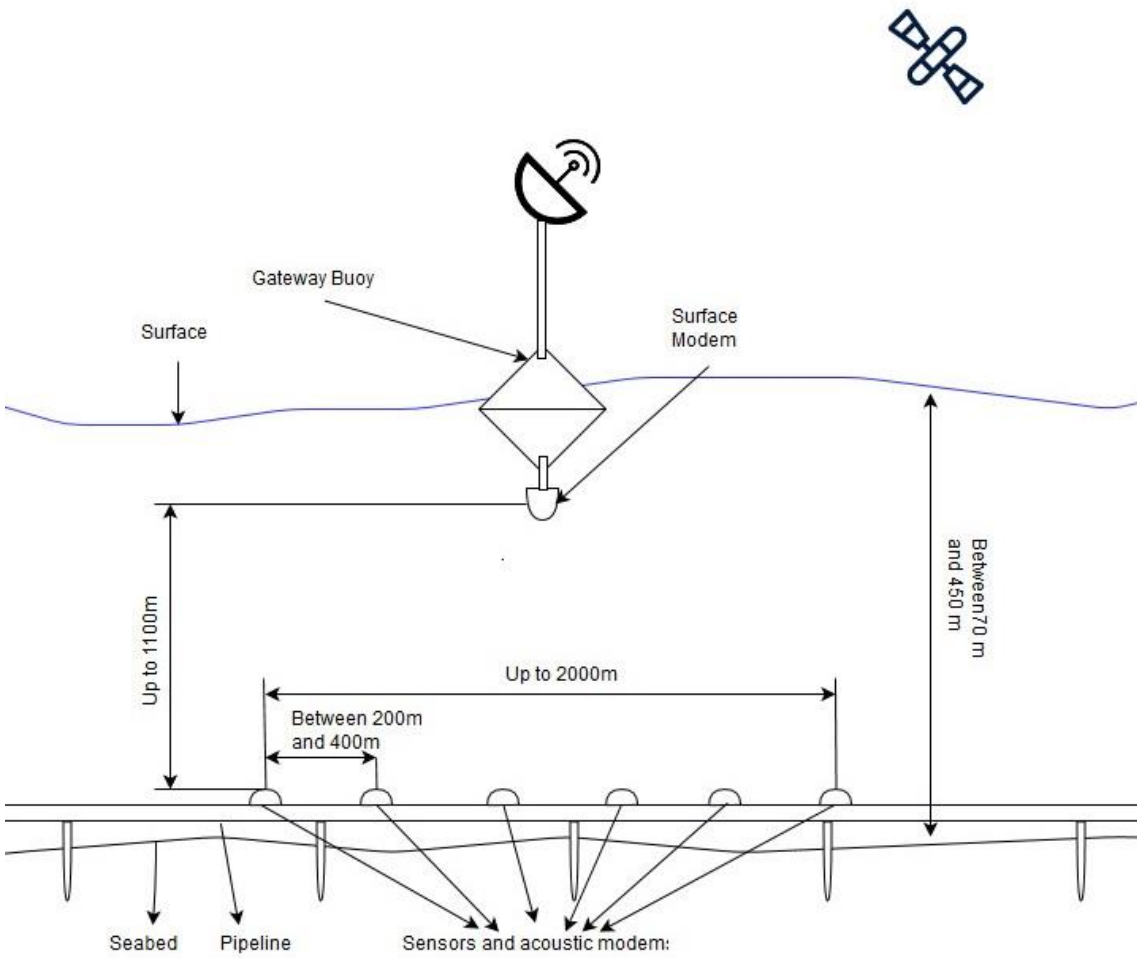


Figure 5.1: Components and distance measurement for underwater network

5.1.2. Acoustic Modems

Underwater Acoustic Modems technology, unlike terrestrial RF modems, is not a widely developed field. There is only a dozen developed by researchers and a few commercially companies developed acoustic modems. This shortage is due to the high cost of equipment and complexity of the environment. Acoustic modem designers need to face severe problems in an underwater environment such as limited bandwidth, harsh environment and high latency.

As shown in Figure 5.2, the underwater acoustic modem needs to possess the following parts:

- Control computer unit with a processor and memory: This unit controls all parts of the acoustic modem and stores sensed data.
- Power supply: In the underwater environment there are limited options for recharging.
- The transducer: It receives and sends signals.
- Analog to digital converter (ADC): ADC converts received analog signal to a digital signal and forwards to control unit.
- Digital to analog converter (DAC): DAC converts digital signal from control unit to analog signal and forward it to transducer.
- Serial or some other interface: This interface connects modem with sensor unit.

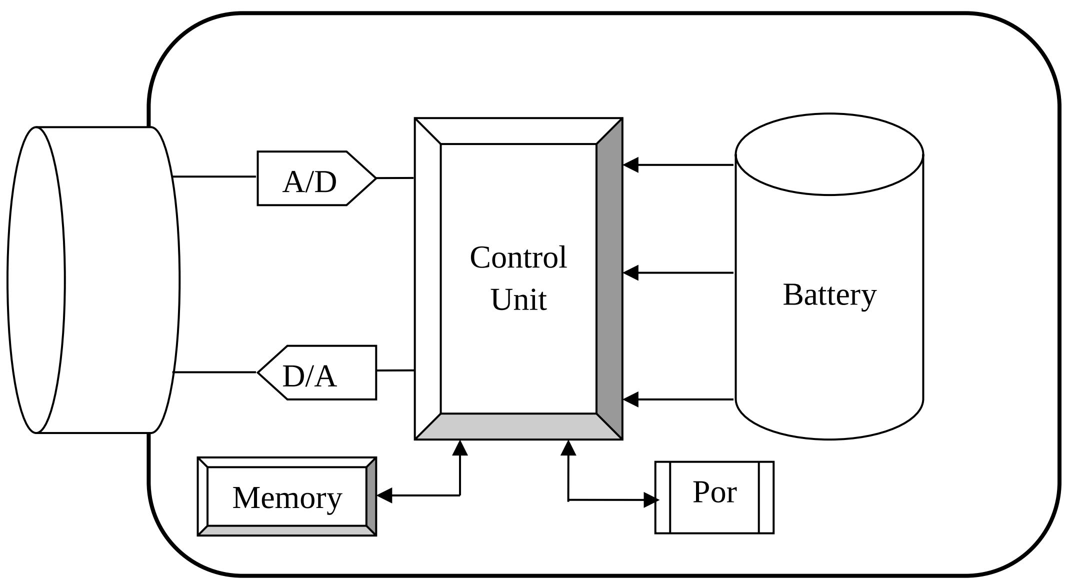


Figure 5.2: Underwater Acoustic Modem diagram

The main problem with an underwater acoustic modem is the power supply. Modems are designed to run on batteries, but in the underwater environment there is no possibility to recharge it. Unlike the terrestrial environment, where it is possible to use solar, wind and waves' energy to charge batteries, the underwater environment does not provide any simple solution for recharging. Today underwater acoustic modems consume more energy compared to terrestrial, and providing long-term deployment can be a challenge. To extend the lifetime of modems, designers have to increase battery capacity. This solution is simple, and it is an easy way to prolong the lifetime of the system, but this approach increase the production and deployment costs of system. Also, it is not practical just to increase battery capacity, especially in a long-term deployment. The more convenient way is to reduce the modem power consumption. That can be achieved by designing and implementing tailored protocols that will better tackle problems in the underwater environment. To reduce battery consumption bit rates and transmission range should be specially tailored for underwater environment parameters such as water pressure, temperature, salinity and depth. Longer transmission range requires higher transmission power. Data transmission requires more energy than data receiving and an idle state, so transmission efficiency should be as high as possible. Commercial modems are mostly equipped with RS232 serial communication port or Ethernet port. These ports are used to configure the modem and to connect with sensors equipment. Commercial solutions have multiple ports and allow several sensors connected to a single acoustic modem. Transducers for modems can be omnidirectional or directional. Typical directional transducers are with a 60-degree angle or with the wide 100-degree angle. With directional transducer modems save energy, can achieve higher efficiency and longer transmission range. Also, with directional transducers, the system reduces the interference between modems. In difference to the directional transducer, omnidirectional one has lower efficiency and transmission range but can cover multiple modems; they are the best solution for the surface sink modem. All these parts should withstand the harsh underwater environment. Pressure, corrosion from saltwater and other environment problems should be considered in the design of housing for the acoustic modem.

The task of acoustic modems will be to transfer information from seabed sensors to the surface buoy. Every sensor on the seabed will be connected with a serial link (RS232) with one acoustic modem, and every acoustic modem will have acoustic link connection with acoustic modem mounted on the surface buoy. For PIG tracking, real-time communication is required. In this phase, seabed modems will immediately forward any information received from the sensor to the surface acoustic modem. In the second phase, pressure monitoring, real-time communication is not required. Acoustic modems will store data from the sensor and forward it to a surface buoy after a specified time (for example at every 2-3 minutes). Seabed modems should be deployed with a housing made of a durable material. Most of the commercial solutions use aluminum or stainless steel as the material to produce housing; these materials are durable and corrosion resistant. For the acoustic modem mounted on a buoy, the housing can be made from the same material as seabed acoustic modem housing or, another cheaper solution can be used, for example plastic housing.

As seen from Figure 5.1, acoustic modems need to fulfill the following system requirements:

- Up to 500 m operating depth
- Up to 1110 m transmission range in near vertical channels
- Good track record
- Build for harsh environment
- Energy efficiency
- High bit rates
- Low error rate

Four manufacturers of underwater acoustic modems will be considered:

- EvoLogics [40]
- DSPComm [41]
- Teledyne Benthos [42]
- LinkQuest Inc. [43]

EvoLogics

EvoLogics underwater acoustic modems provide excellent performance using Sweep-Spread Carrier (S2C) technology, developed by EvoLogics GmbH. Modems use adaptive algorithms to customize configuration (for example bitrate) to current environment conditions, also they have implemented forward error correction (FEC) and energy efficient modules. Wake-Up module turns on the device if detects acoustic signals or incoming data on serial port RS232. After transmitting or receiving is over, the module turns off the device again to save energy. EvoLogics provides plastic, aluminum, stainless steel and titanium housing. EvoLogics modems S2CS2C R 18/34 and

S2C R 42/65 fulfill system requirements. These two models have been shown in Figure 5.3. Modem S2CS2C R 18/34 uses 18 - 34 kHz frequency band and allows up to 14 Kbit/s acoustic link with low bit error rate. This modem is highly energy efficient and consumes only 2.8 W in the transmission mode on 1,000m range and uses an omnidirectional transducer. Modem S2C R 42/65 works on higher frequency, 42 - 65 kHz, and also has a higher transmission bit rate, 31 Kbit/s, but energy efficiency is lower; in transmission mode on 1,000m range this modem spends 18 W. S2C R 42/65 S2C R 42/65 uses directional beam pattern with a wide angle (100 degrees), perfect for vertical communication.

(a) EvoLogic modem model S2C R 18/34

(b) EvoLogic modem model S2C R 42/65

Figure 5.3: EvoLogic underwater acoustic modems taken from [40]

DSPComm

DSPcomm produces highly reliable Aquacomm underwater acoustic modems using new digital signal processing technology. Aquacomm modems use Direct Sequence Spread Spectrum (DSS) and Orthogonal Frequency Division Multiplexing modulation (OFDM), modulation techniques with CRC16 (Cyclic Redundancy Check) error detection to ensure smooth acoustic communication. Aquacomm modems have two configurations of underwater housing. In the first configuration housing can be with a modem and an integrated transducer. In this case battery is external. In the other housing configuration case all three components are integrated into the extended housing. The housing material can be plastic with maximum depth up to 300m; it also can be aluminum (1,000m maximum depth) and Super-Duplex steel (up to 5,000m depth). From DSPcomm manufacturers, modem Aquacomm 480 satisfies the system requirements. This modem has 480 bits/s bit rate and uses 16 - 30 kHz frequency band. The modem can be used for communication at big distances, the vertical range of modem is 3,000m and the horizontal range is 1,000m. Auqacomm 480 modem is highly energy efficient and consumes only 1.8 W in the transmission mode. The problem with this modem can be a low bit rate compared to other modems.

Teledyne Benthos

Teledyne Benthos is a renowned company for subsea solutions; their ATM 900 modem series is well-known for reliability and durability (Figure 5.4). Benthos modems use convolutional error correction codes to encode data and repair any error that appeared during transmission, and Multiple Frequency Shift Keying (MFSK) and Phase Shift Keying (PSK) as modulation schemes. Benthos modems work on multiple frequency bands; it can be chosen between Low Frequency (9 - 14 kHz), Medium Frequency (16 -21 kHz) and Band C Frequency (22 - 27 kHz). The housing is made of Polyvinyl Chloride (PVC) or aluminum and can withstand 500m depth for PVC and up to 6,000 m depth for aluminum. Modem ATM 915 satisfies the requirements for the surface modem, and for seabed modems, ATM 925 is an appropriate solution. ATM 915 uses PVC housing, has the communication range between 2,000 and 6,000m and can achieve up to 15 kilobits/s bit rate. ATM 925 has similar characteristics as ATM 915; the only difference is in the housing material (aluminum). Benthos modem can adjust the transmit power, at the highest level the modem consumes 20 W.

(a) Benthos modem model ATM 915 (b) Benthos modem model ATM 925

Figure 5.4: Benthos underwater acoustic modems taken from [42]

LinkQuest Inc.

LinkQuest company is the manufacturer of SoundLink cutting edge underwater acoustic modems (Figure 5.5). For the purpose of design modems company developed proprietary Broadband Acoustic Spread Spectrum (BASS) modulation technology to tackle problems in the underwater environment. Modems perform at very low bit error rate and have the capability to connect up to eight instruments on one modem. Modems UWM 2000 fulfill system requirements, and UWM 2200 can be considered when the higher bit rate is necessary and distance is less than 1,000m. UWM 2000 modem works at 26.77 - 44.62 frequency and can reach up to 17 kilobits/s bit rate. The modems maximum transmission range is 1,200 m with the omnidirectional transducer and 1,500m with the directional transducer. This modem is energy efficient and consumes between 2 and 8 W depending on transmitting power. Model UWM 2200 works on a higher frequency, between 53.55 to 89.25 Hz, and also achieves higher bit rate, up to 36 kilobits/s. These improvements also have some side effects. The modem has reduced transmission range (up to 1,000m) and consumes more energy (between 6 and 8 W).

Figure 5.5: LinkQuest underwater acoustic modem taken from [43]

Acoustic Modem Summary

In Table 5.1 summarized comparison of the modems mentioned above has been shown. The comparison has been performed regarding bit rates, maximum transmission range and operating frequency.

The problem with these modems is property technology. Because of this, it is not possible for perfectly customized protocols to adapt to specific problems. DSPcomm is a new company in the field. They produce long range power efficient modems, but with relatively low modem bit rate and modest track of record. Because of these characteristics, this modem is not recommended. EvoLogics, LinkQuest Inc. and Teledyne Benthos modems have a good track of records and pass primary requirements of oil companies. Also, all other characteristics of these three modems satisfy fundamental requirements of the task.

Table 5.1: Performance characteristics of acoustic modems

Modem model	Bit rate	Bit error	Max depth (m)	Max range (m)	Transducer type	Frequency operation (kHz)	Port	Modulation and EC
Manufacturer of Equipment: Link-Quest Inc.								
UWM 2000	Up to 17 Kbits	10^-9	2000-4000	1200-1500	Omnidirectional and directional	26.77 to 44.62	RS-232	BASS
UWM 2200	Up to 36 Kbits	10^-9	1000-2000	1000	Omnidirectional and directional	53.55 to 89.25	RS-232	BASS
Manufacturer of Equipment: DSPComm								
AquaComm 480	Up to 480 bits	10^-6	1000	3000	Omnidirectional	16 - 30	RS-232	DSSS/OFDM, CRC16
Manufacturer of Equipment: Teledyne Benthos								
ATM 910 and 920 series	Up to 15 Kbits	10^-7	500-2000	2000-6000	Omnidirectional and directional	9 to 14 ,16 to 21 and 22-27	RS-232	MFSK and PSK, Convolution
Manufacturer of Equipment: Evo Logics								
S2CR 42/65	Up to 31 Kbits	10^-10	2000 With steel Housing	1000 (2000 In good conditions)	Directional with wide angle 100°	42 to 65	RS-232 and Ethernet	S2C
S2CR 18/34	Up to 14 Kbits	10^-10	2000 With steel Housing	3500	Omnidirectional	18 to 34	RS-232 and Ethernet	S2C

5.1.3. Buoy controller

The controller will be a computer unit which will serve as a transition between the surface acoustic modem and a satellite modem. Also, it will control all equipment on the buoy. Satellite or terrestrial link will be used to the remote access buoy control system and further control of the equipment on the buoy.

For this purpose, an ordinary PC can be used; this is the simplest solution and the cheapest one. This solution will require developing special housing to withstand harsh environmental condition. This simple solution has a drawback in reliability and high-power consumption. Ordinary PC has not been designed for the harsh environment of the sea and that can affect the reliability and performance of components. Also, high power consumption can be a big problem in longer deployments.

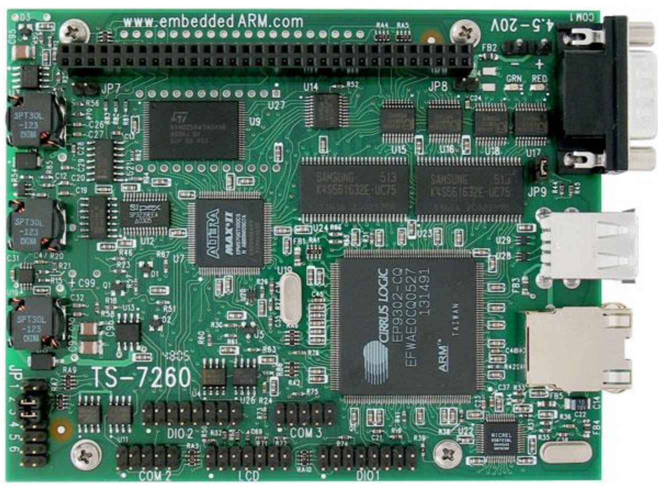


Figure 5.6: Technologic Systems single board computer model TS-7260 taken from [44]

Single board computers (SBC) can be a good solution for the control system. SBC is a fully functional computer integrated on a single circuit board. This type of motherboard is much smaller than the board in PC, and it is designed for industrial power-sensitive systems and other similar applications. In the market, there are a huge number of SBC solutions that can be implemented in the monitoring system. Company Technologic Systems produce SBC modeTS-7260 [44] that fully satisfies the project requirements (Figure 5.6). This SBC is designed for industrial use; it can work in harsh conditions from -40 to +80 Celsius degree. The board had serial ports, USB ports, up to 128 Mb of RAM memory, 32 MB of Flash memory with an option to expand via SD card and the ARM9 processor that work on 200 MHz. This board has by default Linux TS-Kernel 2.4.26

operation system, but it can be changed. The advantages of this board are small power consumption (board spends less than 1 W), low price, and also small size of the board. The disadvantage is that it is necessary to design a special housing for it.

5.1.4. Satellite and RF links

Communication between the surface buoy and a remote host can be achieved using Satellite or terrestrial networks. RF modems as the terrestrial solution can be a good option for real-time communication between the buoy and getaway. They provide a cheap solution, high bandwidth and reliability; RF modems can have a line-of-sight range up to several tens of kilometers. RF modems as the solution can be considered if the buoy is deployed near a coastline or if some sort of gateway (boat, oil rig) is in range. In areas where terrestrial networks are not possible, satellite communication is the only solution.

The use of both RF modem and satellite modem to increase the reliability of the communication system can be an option. RF modem can be used for data transfer if satellite communication fails, and also to quick reconfigure the system from a nearby vessel. A vessel a few kilometers away from the buoy can reconfigure the system quickly using RF modems and without any need to come close to the buoy.

RF modems

At the market today there are a significant number of RF modem producers that can be used as solutions. Company SATEL [45] and FreeWave [46] produce high quality and internationally approved radio networking equipment. They produce RF modems for industrial use with a focus on mission-critical connectivity.

Model SATEL Compact-Proof is a reliable data modem with IP67 [47] (NEMA 6 standard is equal to IP67 standard) housing (Figure 5.7). According to this standard, the modem is resistant to dust, water and formation of ice on it, so there is no need for any additional housing. The modem also has an integrated battery pack that can be recharged and easily replaced. Power consumption is low, 3.8 W while transmitting data and 0.12 W in sleep mode. Working frequency of modem is in 869 MHz range and this frequency is in European ISM (Industrial, Scientific and Medical) band. The modem can work in extreme conditions, from -35 to +65 C, and with maximum range up to

10 kilometers. Advantages of this modem are small power consumption and use of free licenses, and the disadvantage is a relatively small range.

Figure 5.7: SATEL Compact-Proof RF modem taken from [45]

To achieve RF communication at a greater distance, SATELLINE-EASy Pro modem [45] can be used (Figure 5.8). Like the previous modem, SATELLINE-EASy Pro has IP67 certification. Working frequency is between 403 and 473 MHz with three types of channel spacing 12.5, 20 and 25 KHz. This RF modem can cover up to 80 km distance, but with high power consumption. While sending data modem consumes up to 110 W, in sleep mode it is only 0.4 W. This high power consumption is a big problem for the battery power system, but if we consider that the system needs to send a small amount of data and that most of the time the modem will be in idle state (spending only 0.4 W), the modem can be considered as a possible solution. The advantage of the modem is an extremely long range. Disadvantages are power consumption and higher cost due to frequency renting.

Figure 5.8: SATELLINE-EASy Pro RF modem taken from [45]

FreeWave company produces high-quality RF modems, they offer modems as a board level product or enclosed in a rugged housing (Figure 5.9). Modem working frequency is between 2.4 and 2.483 GHz with 12.5 KHz channel spacing. RF data rate depending on modulation, and can be selected between 115.2 kbps (80 kbps low speed) or 153.6 kbps (100 kbps low speed). The power consumption of modem is low, the device consumes 2.5 W during the transmission of data, and in an idle mode less than 0.1 W. This device, that works on 2.4 GHz ISM frequency band, has low power consumption and has data link range up to 32 km, is an excellent solution for long-range data transmission. The only drawback of this device is housing, for deployment in the harsh environment, a better one will be necessary.

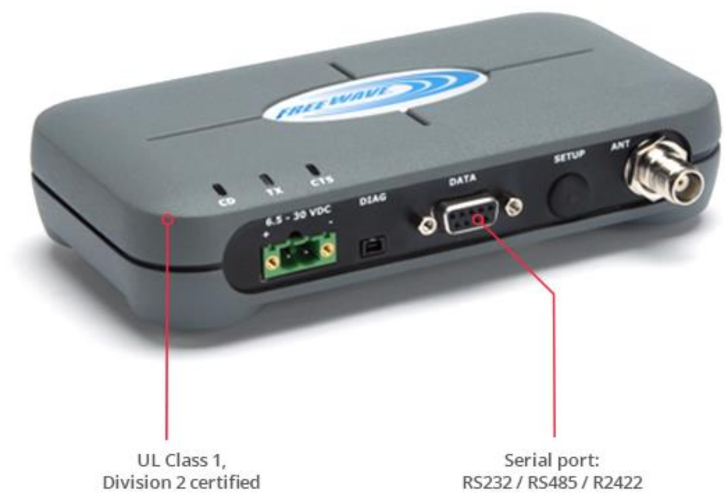


Figure 5.9: FreeWave GX-CE series industrial RF modem taken from [46]

To achieve long distance communication, RF modems need to have a line of sight. Without clear line of sight, range of equipment significantly decreases. To accomplish long-range communication, it is necessary to carefully decide the position of modems to avoid any obstacles between two modems. In addition to obstacle avoidance, it is also necessary to place modems at the appropriate height to achieve line of sight; this is due to the curvature of the earth. Placing antennae at higher altitudes provides longer communication links. Using Equation 3.3, in Table 5.2, it has been shown which line of sight distance can be achieved with different heights of antennae. The first column represents antenna that is placed on a buoy, and its height is fixed to 3 meters.

Table 5.2: The line of sight distance for different height of antennas

First antenna height (m)	Second antenna height (m)	First antenna radio horizon (km)	Second antenna radio horizon (km)	Line of Sight (km)
3	10	7	13	20
3	20	7	18	25
3	30	7	23	30
3	40	7	26	33
3	60	7	32	39

Satellite modems

The primary way of sending data from a buoy to a remote location will be using satellite communication. Unlike RF solutions, satellite networks can provide coverage in any position on the earth. Satellite networks for data transfer are mostly LEO or GEO constellations.

The Iridium Company provides Short Burst Data (SBD) service [48]. This is a simple satellite service for transmitting small data messages from field equipment to a remote location. SDB architecture consists of a satellite modem, satellite constellation, the Iridium gateway on earth, the Internet and a remote host application. The Iridium satellite network consists of 66 LEO satellites. These satellites are cross-linked and cover the entire earth, including polar zones.

The second generation of the Iridium modem, 9522B [49] (Figure 5.10) can be used as a solution for data transfer. This modem can be used for several services, including Short message service (SMS), voice telephony, SBD and Circuit Switched Data (CSD). The modem has housing that is resistant to dust, water and high humidity, operating temperature of the modem is from –30°C to +70°C. Operating frequency is between 1616 to 1626.5 MHz and average power consumption during data transmission is 4 W. The maximum size of data messages is 1,960 bytes for mobile originated and 1,890 bytes for mobile terminated messages. Average latency from a satellite modem to the Iridium gateway for messages of 70 bytes is 7 seconds, and 20 seconds for the maximum size data messages. The modem does not have an integrated battery; the power source needs to be provided. This modem and SBD service is an excellent solution for near real-time tracking and monitoring application in a location that is not covered by terrestrial networks.

Figure 5.10: Iridium 9522B modem taken from [49]

The Inmarsat is a satellite telecommunications company, which provides telephony and data service via 12 GEO satellites. Its satellite service IsatData Pro [50] is Machine to Machine (M2M) communication system that provides reliable and fast two-way data exchange. This service can be accessed via small, low power consumption terminals that can be easily implemented in various applications.

Figure 5.11: SkyWave IDP-690 modem taken from [51]

The Skywave IDP-690 terminal [51] (Figure 5.11) is a reliable and easy to install device, to access IsatData Pro services. The terminal is designed for maritime low energy consumption systems (consumption is up to 9 W), with low evaluation angle which is suitable for the satellite communication in near-polar regions. Device housing has the IP67 certification and can withstand harsh environmental conditions, operating temperature of the modem is from –40°C to +85°C. Terminal operates at two different frequencies, for transmitting data the used frequency is between 1626.5 and 1660.5 MHz and for receiving data between 1525.0 to 1559.0 MHz. The terminal's maximum data messages size is up to 6,400 bytes for mobile originated and 10,000 bytes for mobile terminated data messages. The latency is less than 15 seconds for data messages smaller than 100 bytes.

Iridium services and devices have lower power requirements and smaller latency; this is due to the use of LEO constellation. To achieve better reliability of the system, Iridium and Inmarsat services can be used together. The Iridium satellite network can be used as a primary way of communication and Inmarsat can be used as a backup.

5.1.5. Buoy system

The Buoy is floating structures equipped with telemetry equipment; it represents gateway between underwater network and surface network. Buoy needs to be anchored to the seabed in order to remain in the range of seabed acoustic modems. Depending on the design, a buoy can be used in coastal or offshore waters. Buoy system needs to be easy for deployment and retrieving, and special attention should be given to corrosion and biofouling. These two problems can significantly reduce the lifetime of the entire system.

The buoy system is composed of the following components:

- Hull
- Mooring system
- Power recharging system

Hull is a part of the buoy system that ensures floating of the complete structure. It needs to be big enough to host all equipment and robust to withstand harsh condition on the sea. According to [52] shape of buoys can be boat-shaped, toroid, Bumblebee shape, discus and spar, but today in the ocean observation system, discus and spar buoys are mostly used. Hull can be made of steel, aluminum or plastic and needs to be equipped with light signaling equipment according to law.

Mooring can be divided into two parts, anchor and mooring lines. The anchor is used for maintaining hull in one position. The hull will still move with currents, tides and waves, but the job of mooring system is to constrain those movements to a small area, and that area is centered round the anchor. When selecting the shape and weight of an anchor, several aspects must be taken into account. It is important to know the environmental conditions of the deployment area, the size and weight of the buoy system and the structure of sea floor. The anchor needs to provide enough holding power to hold the buoy at the same place even in extreme conditions. Mooring line needs to be durable enough to withstand winds, tides and currents. During mooring line design various conditions must be taken into consideration. The following terms must be considered: depth of water, environmental conditions, design life, fishbite and special conditions, like the distance to fishing area. Mooring line can be made of metal, synthetic material, or combinations of these two, and typical single-point mooring system and three-point mooring system are in use. Single-point mooring system is used for smaller buoys and contains a single line of rope from the surface buoy to the seabed anchor. Three-point mooring system is used for large buoy systems and deployment is much more complicated than a single-point. This system contains three separate ropes connected to three anchors on the seabed.

In order to ensure long deployment of the buoy, recharging batteries capabilities can be implemented. This can be achieved via solar panels, wind turbines or using wave's energy. Depending on environmental conditions these systems can provide multiannual lifetime to the buoy system.

At the market, there are a lot of buoy ocean observatory solutions that can be used for underwater pipeline monitoring system. It will be further explained by means of Teledyne Benthos Gateway buoy [42], specially designed for seabed to surface communication, and DeepSea MKI-3 [53], DB 4700 [54] and G-3000 [55] ocean observation buoys.

Teledyne Benthos Gateway Buoy

Manufacturer of the underwater acoustic modem, Teledyne Benthos, also produces gateway buoys (Figure 5.12). This relatively small buoy with hybrid spar and discus shape is equipped with radio modem that works at the free frequency or Iridium satellite modem. The buoy also has integrated power supply, four 12-volt sealed lead-acid batteries. Batteries are rechargeable, but there is no possibility of installing solar panels on the buoy. Because of the small size of the buoy, only two persons are enough for the buoy deployment. However, also because of the size, the buoy is not the best choice for long offshore deployment. The buoy is also equipped with signaling lights, and mooring for the buoy is not provided by Teledyne Benthos.

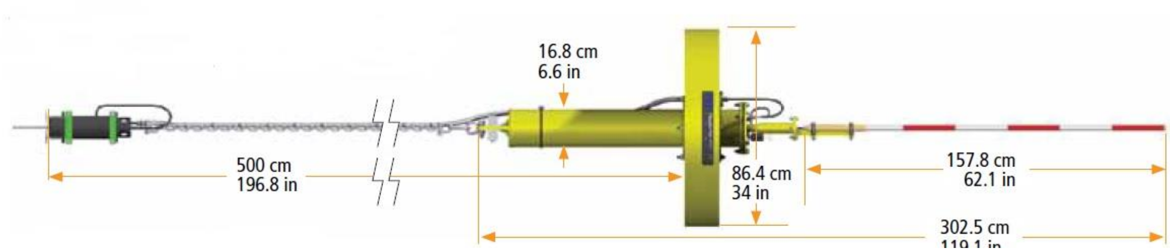


Figure 5.12: Measurements of Benthos Gateway Buoy taken from [42]

Deep Sea MKI-3

Deep Sea MKI-3 is the ocean observatory buoy manufactured by Envirtech. The buoy is made from stainless steel, and it has discus shape hull. It is a highly durable system for long-term deployment with various data sensing and telemetry options. The company provides several solutions for data transfer, Radio modems (VHF/UHF RF with from Power 0.1 to 5 W), Inmarsat M2M, Iridium and GSM. Buoy power supply is Gel Batteries (320 W), and in combination with solar panels, it can provide multiannual deployment.

DB 4700

DB 4700 buoy is similar to Deep Sea MKI-3. This system is designed and manufactured by AAnderAA. The main difference is in size, material and telemetry options. This buoy is smaller than MKI-3 buoy and hull material is polyethylene instead of stainless steel. DB 4700 buoy provides more Telemetry options than MKI-3, for satellite data transfer the buoy uses Argos, Orbcomm and Iridium satellite modems.

G-3000

Mooring Systems, Inc. produces surface buoys for the use as platforms for oceanographic and meteorological instruments. They do not provide communication devices or sensors together with buoys; they produce platforms on which the equipment can be placed. G-3000 buoy base is made of steel, and the buoy tower is made of aluminum. This combination ensures durability of the buoy system in a harsh environment. The buoy has a waterproof compartment that is intended for mounting batteries and electrical equipment. The diameter of the buoy is 2.1 m, and the overall height is 3.5 m. Mooring Systems, Inc. also provides radar reflector, solar light and mooring.

Figure 5.13: Mooring Systems, Inc. Guardian G-3000 buoy taken from [55]

5.1.6. Power requirements

The power for the system comes from battery packs. The power requirements of seabed equipment are more challenging than the surface equipment; this is due to the requirements of small batteries size and the absence of ways for batteries recharging. Power solution for sensors equipment already exists, so the focus will be on the equipment for data transmission. Batteries for acoustic modems need to fit into a waterproof housing together with a modem, or in a separate waterproof housing, so the size of the battery needs to be carefully determined. Also, compared to a terrestrial environment where batteries can easily be recharged, using solar wind or some other way, in an underwater environment this is very limited. All these limitations lead to a limited batteries capacity. Therefore the equipment can work within that limited time. To maximize the lifetime of the modem, the power consumption of the equipment needs to be carefully considered.

For underwater acoustic modems transmission requirements define maximum deployment lifetime. Modems that are mostly in idle state and have small transmission requirements can be deployed for an extended period, and modems that need to transmit the vast amount of data have limited deployment time. This is because of the huge difference between the power required for an idle state and the transmission of data, as shown in Table 5.3.

Table 5.3: Power consumption of acoustic modems

Modem model	Transmission consumption	Receiving consumption	Idle state Consumption
Manufacturer of Equipment: Link-Quest Inc.			
UWM 2000	2 W	0.8 W	8 mW
UWM 2200	6 W	1 W	12 mW
Manufacturer of Equipment: DSPComm			
AquaComm 480	1.8 W	0.25 W	1.8 mW
Manufacturer of Equipment: Teledyne Benthos			
ATM 910 and 920 series	20 W	0.76 W	16 mW
Manufacturer of Equipment: Evo Logics			
S2CR 42/65	18 W	1.1 W	2.5 mW
S2CR 18/34	35 W	1.6 W	2.5 mW

With low power consumption in an idle state, modems at the seabed can work for more than several years. For the first phase of monitoring of underwater pipelines, PIG detection, modems need to send a small amount of data. Every modem needs to send 1 byte of data and that only a few times for full deployment. With a small amount of data transmission and only a few days of deployment, this phase can be neglected. The second phase, transmission of pressure data, modems needs to send larger amounts of data and power consumption can be a problem.

In the second phase of monitoring, sensors gather pressure data every second and each second data will be up to 3 bytes big. This data will be collected and forwarded to the surface at every two minutes, so one packet of data will be 360 bytes. To calculate the necessary capacity of the battery, the following equation can be used:

$$C = d * p/(s * 450) \tag{5.1}$$

where d is the amount of data (byte), p is transmitter power consumption (W) and s is bit rate (bits/second).

If modem has a battery capacity of 250 W (capacity of alkaline batteries for Benthos modems [42]), sending data with bit rate of 1200 bits per second (lower speed due to bad conditions) and with transmitter consumption of 20 W (maximum power consumption of Benthos modems), for pressure data transmission in 24 hours, the modem will spend only 9.6 W. This leads to the conclusion that 250 W batteries capacity is more than enough for a short deployment. Also, the fact that batteries at 0 degrees Celsius have 25 percent less capacity [56] should be taken into consideration.

5.1.7. Cost of equipment

Table 5.5 shows the price of equipment and satellite services which are necessary for the system. The table does not include all parts, for example, some cheap parts like battery pack for the buoy and cables have not been shown. Also, the price of buying a license for RF modem frequency band has not been included. RF modem that uses license-free frequency band is recommended. Complete equipment for the system can cost between 72,000 $ (system with three acoustic modems) and 135,000 $ (a big system with seven acoustic modems, six on the seabed and one on the surface) plus approximately 2,000 $ for accessories. Satellite services after a one-time activation fee will be up to 200 $ per deployment. Satellite companies count one kilobyte of data as 1,000 bytes instead of 1,024 bytes as it is in standard systems.

5.1.8. Instruction sequence of deployment

Before its deployment, the equipment needs to be tested and configured. To configure acoustic modems, it is necessary to turn them on (for example Benthos modems have on/off switch on the housing) and connect the modem to some host processor. For this purpose, it can use a regular PC with a serial port and terminal program on it. It is necessary to configure parameters such as transmission rate, ID address of the modem and the power of signal before deployment.

After configuring, it is necessary to check receiving capability of the modems. For most modems, it can be verified while configuration mode between the PC and the modem is on. Modems have an embedded system to test the transducer. A transducer needs to be gently tapped, and if gained value is changing at the terminal, the test has been passed.

Table 5.4: Cost of equipment and satellite services

Equipment price			
Part of system	Name of equipment	Price per unit	Description
Buoy	Mooring Systems G-3000	17,500 $	Platform for surface communications equipment.
Acoustic modem	Evologics S2CR 42/65	Up to 16,000 $	Complete acoustic modem with housing, battery pack, transducer and cables.
Buoy controller system	Technologic Systems TS-7260	200 $	Single board computer with Linux operation system
RF modem	FreeWave GX-CE	1,500 $	RF modem with housing
	Satel EASy Pro	2,300 $	RF modem with housing
Iridium SBD modem	9522B	1,300 $	Satellite modem with housing
IsatData Pro modem	SkyWave IDP-690	900 $	Satellite modem with housing
Satellite services rates			
Service	Activation fee	1000 bytes price	Monthly fee
Iridium SBD service	50 $	1.2 $	18 $
	50 $	1.2 $	35 $ (30 Kbytes per month include)
IsatData Pro service	250 $	2.5 $	8.75 $ (1 Kbytes per month include)
	250 $	0.5 $	90 $ (100 Kbytes per month include)

For the deployment of buoy and seabed equipment, a boat and ROV is required. Buoy needs to be moored in the middle of the testing area to provide adequate distance to all seabed modems, for that purpose a boat can be used. To deploy seabed equipment ROV needs to be used. All equipment needs to be accurately located on the seabed and retrieved using ROV. This implies positioning sensors and modems on underwater pipes and securely attached to the structure. For retrieving equipment, acoustic releases system can be used instead of ROV.

Equipment can be tested after deployment or at any time using integrated protocols for testing. It is necessary to remote access control computer on the buoy and use command line ping any modem on the seabed from the surface modem.

Also before deployment, battery capacity should be checked. Battery capacity is decreased over time whether it used or not. Benthos recommended changing batteries every two years. After two years of use, battery capacity drops down to 90% and it is no longer reliable for long-term use.

5.1.9. Modularity and reliability of subsea nodes

Modularity of subsea nodes can extend the possible application of the system. Also, with the modularity of nodes, they can easily adapt to different conditions that may occur at various testing locations. To achieve that, equipment of nodes needs to be housed in separate housings. Deployment of a large number of equipment items is not an easy task, so to further facilitate deployment, standardized frame for mounting equipment needs to be designed. All equipment from one node needs to be mounted on this frame, and the frame needs to be designed for harsh environment and simple deployment on the pipeline. The advantage of this solution is that equipment can be easily deployed at the test location, also changing and upgrading of the new equipment can be done without the need to redesign nodes.

Temporary losses of connectivity can be a huge problem for the reliability of the system. This can happen due to shadow zones or some other obstacles on the signal path. In systems where reliability is the primary requirement when temporary losses of connectivity happen, another way to transfer data needs to be found. The simplest possible solution for this problem is using more modems to achieve redundancy. Using this solution, the system will increase reliability, but the cost of the system will increase significantly. Another way to deal with temporary losses of connectivity can be rerouting. If a node detects that vertical link is down due to some obstacle on the path, path of data transmission can be changed. This can be achieved by implementing routing protocol in the system. Using routing protocol, after detection that vertical link is down, the node can send data to the neighbor node, and the neighbor node will further forward data to the surface gateway. This solution will improve the reliability of the system, but with increasing delay and complexity of the system.

5.1.10. Summary

The complete system consists of a buoy, seabed sensors, acoustic modems, RF modem, satellite modems and buoy controller and software solutions.

Type of the buoy for the system needs to be decided depending on the location. For near coastline location, Teledyne Benthos Gateway Buoy can be used as a complete solution with integrated communication equipment. This buoy is lightweight and easy to deploy. Having in mind that most of the operation will be performed on an offshore location, a buoy for the offshore environment is necessary. Deep Sea MKI-3 and DB 4700 are ocean monitoring buoys with integrated equipment for monitoring environment, these buoys can use as a solution, but the price is the main disadvantage. G3000 is offshore buoy designed to be a platform for instruments. Manufacturer provides buoy with mooring system and lights as accessories. This buoy can be a satisfactory solution for offshore deployment of the system.

Sensors are provided by Halliburton from the previous monitoring system. These sensors need to be adapted for the new system; it is required to integrate cable for data transfer to the acoustic modem.

Table 5.5: List of customers of EvoLogics, LinkQuest Inc. and Teledyne Benthos modems

Manufacturer	Customers
EvoLogics	A list of some customers (non-exhaustive, recent purchases): Independent Robotics (Canada), Center for Maritime Research and Experimentation (NATO Italy), IFREMER (France), **Pinnacle / Halliburton (USA)**, Offshore Sensing AS (Norway), ECA Group (France), Atlas Elektronik (Germany), JT Elektrik Trawlcamera Faroe (Islands), JAMSTEC (Japan), MLD APs (Denmark), RPS Metocean (Australia)
LinkQuest Inc.	A list of some customers, a complete list can be found on [43]: Fugro Chance, Fugro Survey, BP, Shell, ExxonMobil, Petrobras, Total, Schlumberger, Heerema, Allseas, Boskalis, Marathon, Kongsberg, Boeing, Oceaneering, C&C Technologies, Lockheed Martin, Mitsubishi, Fugro GEOS, Fugro Seafloor Survey, Fugro Marsat, Fugro Geonics, Seatools, 2H Offshore, Institute of Marine Research (Norway)
Benthos	Official information not available.

EvoLogics, LinkQuest Inc. and Teledyne Benthos reputable acoustic modem manufacturers. These companies produce modems that have a good track of record and specification, and they meet all the requirements of the system. Modems come as a ready-to-use product with all accessories (batteries, housing, transducers, cables, etc.). As shown in Table 5.6, for Teledyne Benthos modems there is no official information about clients which are available to the public, but regarding the reputation of the company and the information found on the Internet, it can be concluded that they have an equally good track of record as EvoLogics and LinkQuest Inc. Although all three manufacturers have good products that can be implemented in the system, the recommendation is to use Benthos modems, which are well known in the oil industry.

For surface communication, RF modem and satellite modems can be used together or depend on the case one of them can be mounted on the buoy. Priority should be given to RF modem, which is cheaper, more reliable and with lower latency than satellite modem. For RF modem, FreeWave GX-CE modem is a satisfactory solution. This modem has low power consumption and can establish up to 32 km long point to point link. FreeWave also produces modems with longer range than GX-CE modem, but for that, it is necessary to pay for frequency license. Also, according to Table 5.2 when this modem is used for extreme long-range links, it is required to mount the modem antenna on the higher ground, and that can be hard to achieve in such environment. Satellite communication can be established using Iridium LEO constellation or Inmarsat GEO constellation. Iridium SBD service provides a lower latency than Inmarsat IsatData Pro service, so Iridium should take priority. Also, the usage of both services can be considered in order to increase the reliability of data transfer.

To manage the buoy system, it is required to implement a control unit on it. For that purpose, it is recommended to use the single board computer TS-7260. This controller is designed for power-sensitive systems and can be easily adapted.

To implement a system completely, it is necessary to develop software solutions for handling data on a remote host and the data transfer from the sensor to the acoustic modem and from the acoustic modem to the satellite modem (RF modem). Satellite services or RF modem will be used for data delivery to a remote host. In order to process and analyze these data, the software solution is necessary. The solution on the remote host needs to process the received data and provide a graphical view of the data to the user.

Software and hardware on seabed sensors need to be upgraded for the data transfer from the sensor to the acoustic modem via a serial cable. In PIG detection monitoring task, the sensor needs to send information immediately to the acoustic modem, and the modem will forward that information further. In a task where pressure data needs to be transferred, the sensor will send data immediately to the acoustic modem and then the acoustic modem will forward them, when it receives a request from the surface.

For the buoy controller unit, software solution also needs to be developed. This solution will store all data from seabed sensors and transfer the data from the acoustic modem attached to the buoy to surface communication modem.

Although it is designed for a specific task, this system is highly usable and with little reconfiguration it can be used in many applications. Improvement possibility is also good, depth and communication range can be improved significantly on demand. This system is designed for the depth up to 450 m, but the range can be extended. EvoLogics, LinkQuest Inc., and Teledyne Benthos modem manufacturers have products that can work and communicate at several thousand meters depth. To extend the use further, additional equipment can be mounted on the buoy, for example, temperature sensors and pressure sensors. The system is designed to be easy to use, maintain and upgrade.

5.2. The Improvement of the COTS technology

To achieve better performance, acoustic modems need to be modified, because PIG tracking and pressure monitoring are two very different tasks. Therefore, COTS should be adapted for each of these tasks**.** In PIG tracking task, sensors are placed along the pipeline, and their task is to detect PIG when it passes by. During this task, the speed of PIG is very low (0.5 m/s) and the distance between two PIGs is very long. In addition to this, only few PIG are deployed along the pipeline. For pressure monitoring task, data transfer between the seabed unit and the surface buoy need to be scheduled at every few minutes, and data collision between sensors can be easily avoided. According to these specifications, collision probability in this system is very low, and can almost be neglected, MAC protocols should be designed to take advantage of these features.

5.2.1. Packet Format

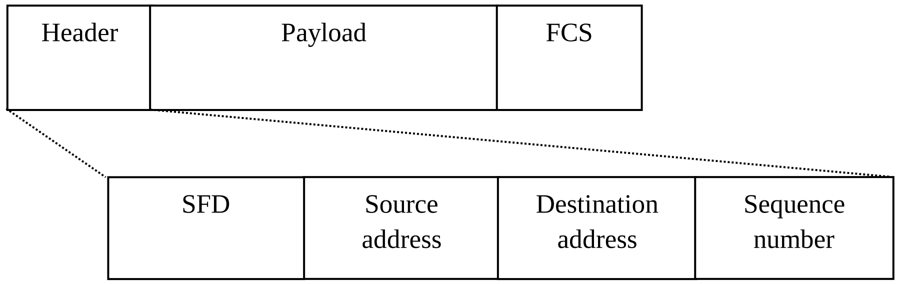


Figure 5.14: The data link layer packet format

As illustrated in Figure 5.14, the Data Link Layer packet contains a header part, data part, and Frame Check Sequence (FCS) part. The packet header includes Start Frame Delimiter (SFD), the source address, the destination address and the sequence number fields. SFD field marks the beginning of the frame, and it is represented by a unique sequence of bits. The sequence number field is a unique number assigned to the packet by the source node. FCS field contains CRC bits; these bits are used for checking of the packet for errors.

5.2.2. MAC for PIG tracking

TDMA-based and CSMA-based MAC protocols in underwater WSN can be an excellent solution for applications where a huge amount of data needs to be transferred, and collision probability is high. However, for the task with low collision probability and a small amount of data, these protocols are not the best solution. Implementing of TDMA protocol in underwater WSN can be challenging, this is due to the variable delay that makes problem with time synchronization and long propagation delay that requires longer guard time periods. CSMA protocols will result in longer delay time; this is due to the requirement for exchange of RTS/CTS packets.

The long propagation delay of signal and small packets size are requirements that perfectly suit random access MAC protocols. Simple protocols such as ALOHA can be a satisfactory solution and variation of original ALOHA protocol, similar to [5], can be adapted to fully utilize all system characteristic.

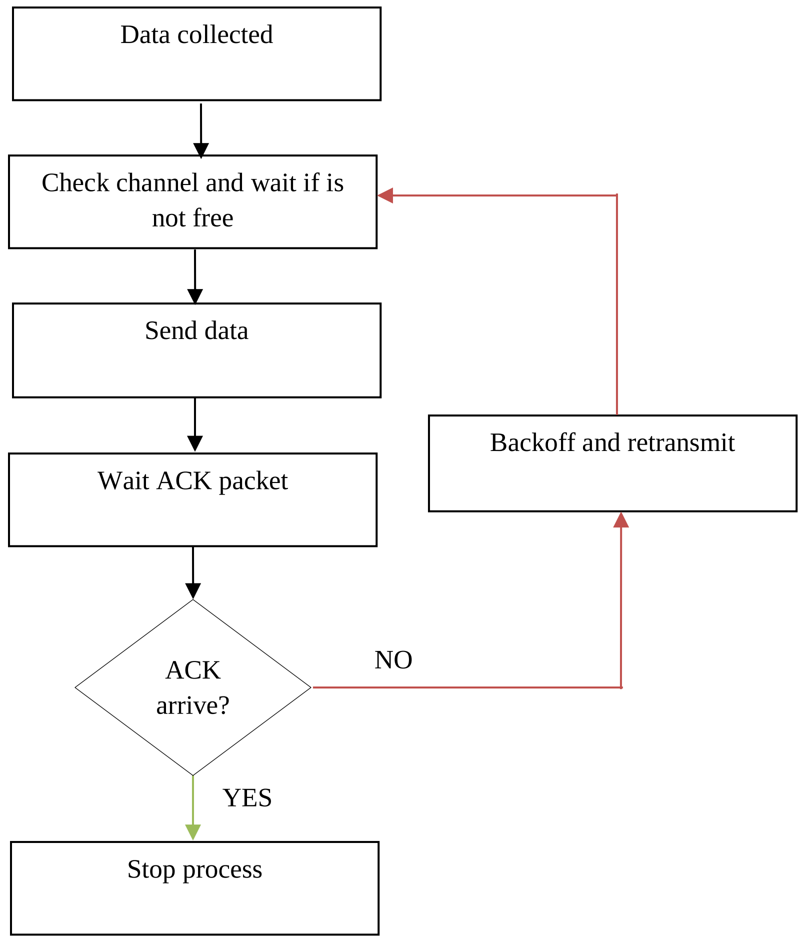


Figure 5.15: Workflow of Hybrid ALOHA/CSMA protocol

Hybrid ALOHA/CSMA protocol from Figure 5.15 use ARQ mechanism to provide reliable data transfer, a back-off mechanism to avoid a collision during retransmission and carrier sensing to decrease the probability of collision. The protocol uses stop-and-wait ARQ scheme and according to this scheme, if the sender does not receive ACK it will be assumed that packet is lost and the sender will retransmit the packet. During this period sender does not send any further packets until it receives an ACK. This ARQ scheme fits perfectly in cases where we have a small amount of packets to send. Like in the original ALOHA protocol, a sender transmits data immediately without handshaking, but before sending protocol will check whether the channel is free. If the channel is free node will send the packet immediately, and if it is not, the node will wait until the channel is free. Carrier sensing option will be only used in the system when nodes use omnidirectional antennae. Without omnidirectional antennae, nodes cannot hear other transmissions and use of carrier sense will give no results. Hybrid ALOHA/CSMA protocol with ARQ, back-off and carrier sensing mechanisms can provide simplicity, small access delay, and reliability to the system.

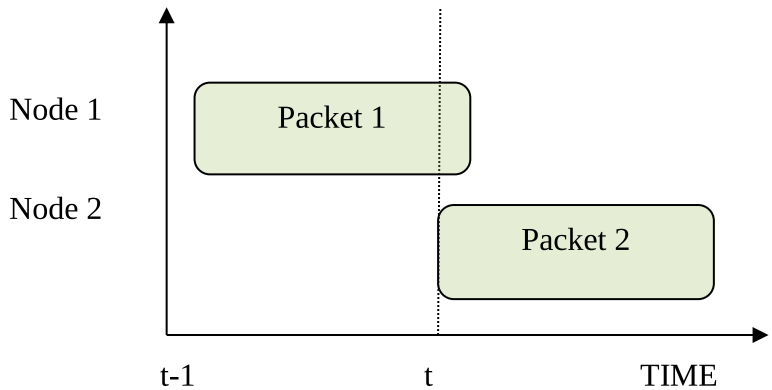


Figure 5.16: Collision in ALOHA protocol

The main difference that makes ALOHA protocol suitable for underwater communication is long propagation delay. In terrestrial communication, propagation delay can be neglected due to the high speed of the electromagnetic signal, but in underwater acoustic communication propagation delay greatly affects communication. For better understanding, propagation delay at 1,500 meters distance for the electromagnetic signal is approximately $5 * 10^{-6}$ second and for the underwater acoustic signal it is approximately *1* second.

In terrestrial communication, as shown in Figure 5.16, a packet sent at time t will collide with any packet sent between $t - 1$ and $t + 1$, but in underwater acoustic communication that is not the case. In acoustic communication, the arrival time of the packet is important, and transmission is without collision if the packet doesn't collide on destination.

5.2.3. Scheduling for pressure monitoring

In pressure monitoring task, data should be transferred from seabed sensor to the buoy at every few minutes. The number of minutes between sending needs to be decided according to requirements of the system. To achieve regular flow of data and power saving, acoustic modem needs to transfer data at every two or three minutes. To avoid a collision in data transfer, if more than one pressure sensor is mounted on the pipeline, pulling of information should be used. Protocol for pulling information should be installed on the buoy controller, and pull data from the seabed unit according to the schedule. In order to obtain data from the seabed, the sensor on pipeline needs to transfer the data via a serial cable to the acoustic modem which needs to be in the data logger mode. This mode will store data in internal memory and forward it at request from the surface. The protocol implemented on the buoy controller will send requests to seabed nodes according to the predetermined schedule. Every request that protocol needs to send will be assigned to agents, and they will perform the algorithm for pulling the pressure data, as shown in Figure 5.17. If the agent fails to pull the data from the seabed node in the predefined time, the agent will send a request to the protocol for rescheduling pulling of data. Using this mechanism, collision between packets will be avoided. Also, to provide reliability of data transfer, negative ACK mechanism should be used as a guarantee that nothing is lost during the transfer.

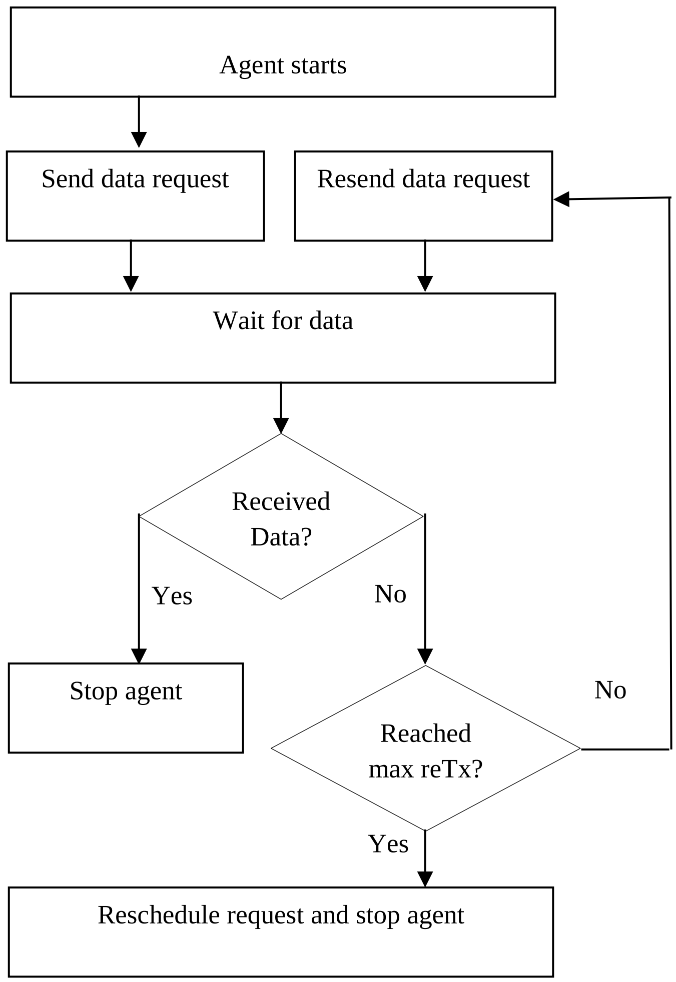


Figure 5.17: Workflow of protocol for pulling pressure data from seabed sensors

6. Simulation and analysis

Performance evaluation of the system is carried out in a simulation environment. The system is tested for a subset of performance measures to evaluate if it meets the design objectives. However, further emulation and real-world testing needs to be performed before finalizing the details of the design.

Simulations are carried out using the SUNSET framework. Because satellite systems use a well-known technology, simulations will be performed only for underwater part of the network. During the simulation, it is assumed that nodes have unlimited queue size. Also, it is assumed that there is no path loss and the packet loss can only be caused by collisions. For all experiments, data rate of the acoustic modem is set to 1,000 bps, the speed of the underwater acoustic signal is fixed to 1,500 m/s, the number of nodes is six and ALOHA/CS protocol is used unless otherwise specified.

6.1. Packet delay

In the first experiment the delay of a packet is simulated. The data packet size is set to 20 bytes, also, in the simulation for every packet, additional 1.2 seconds are included for the acquisition and low-power wake-up (this is according to the characteristic of Benthos acoustic modems [42]).

Figure 6.1 shows an average packet delay in seconds for different distance between the sensor node and the sink node. For this graph, underwater packet delay is simulated, and satellite Iridium SBD delay is taken from [57]. The packet delay is defined as the time between sending the packet from the sensor node and receiving it to the surface sink or end user. The average delay of packets has a steady growth that is caused by increasing the propagation delay in the underwater part of the network. Delay of packets can vary up to 0.8 seconds depending on the distance to the sink node. Acoustic modems with ALOHA/CS protocol achieve minimal delays due to its design to immediately send it if the underwater medium is in an idle state. For networks that have a low collision probability this is a perfect choice. The significant increase of delay, approximately 7.1 seconds, is caused by Iridium SBD and this is due to the characteristic of the service. If this delay proves to be too large for the operation of the system, using other ways of satellite communications can be considered.

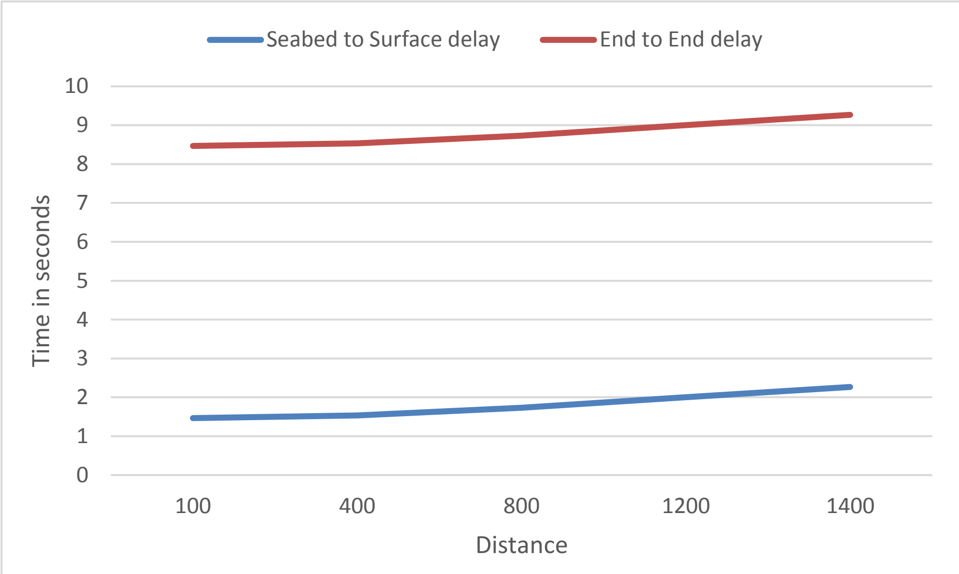


Figure 6.1: Seabed to surface and end to end delay

6.2. ALOHA vs. ALOHA/CS

The second experiment compares two different MAC protocols to explain how carrier sensing mechanism affects the system's throughput.

Figure 6.2 shows throughput of the system for regular ALOHA protocol and Hybrid ALOHA with a mechanism for carrier sensing. In this experiment, regular ALOHA sends packets immediately, and a hybrid version will first check the carrier and if it is free, and packets can be sent. As seen in Figure 6.2, the carrier sensing mechanism improves the maximum throughput of the regular ALOHA protocol, also after reaching the maximum, throughput slower declines than in regular ALOHA. This behavior of Hybrid ALOHA/CS is due to the reduced probability of collision; the protocol will wait if somebody already transfers and thus will avoid a collision and then retransmission of the packet. Under high load, probability of collision is still high, due to a high propagation delay and with that possibility that we cannot hear a transmission that has even started before carrier sensing.

In this experiment, it is assumed that all nodes can hear each other, but in systems in the real world, it depends on the sensing range and the distance between nodes, and it is not necessarily true. If all nodes cannot hear each other, maximum throughput will still be better than regular ALOHA.

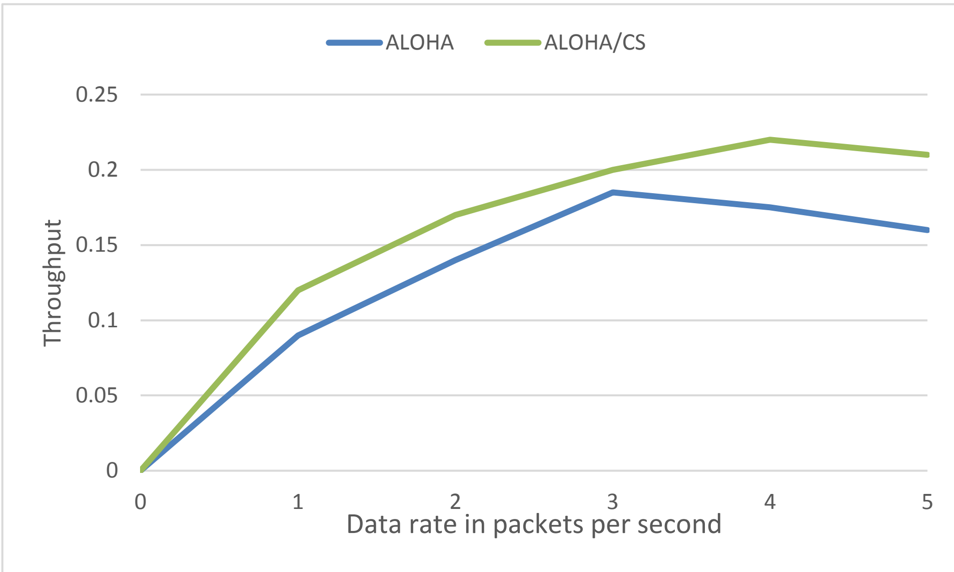


Figure 6.2: Throughput difference for ALOHA and ALOHA/CS.

6.3. Throughput and topology of the network.

In the third experiment, the system throughput is tested with a different number of nodes. The system throughput is tested for six and twelve nodes. The objective of this simulation is to explore the behavior of the system with different nodes density.

In Figure 6.3 it can be seen that ALOHA/CS throughput changes depending on the density of nodes. In a six-node network, throughput relatively quickly reaches its maximum and then slowly decreases. In dense networks, the system quickly achieves maximum throughput, but also after that throughput decreases fast. With increasing number of nodes, the amount of data is increased and along with that, the possibility of collision. With the high probability of collision, throughput starts to decrease quickly due to ALOHA/CS design that doesn't implement smart collision avoidance. From this, it is obvious that ALOHA/CS does not work well under high load conditions, but if the data load is small, it can be an appropriate solution.

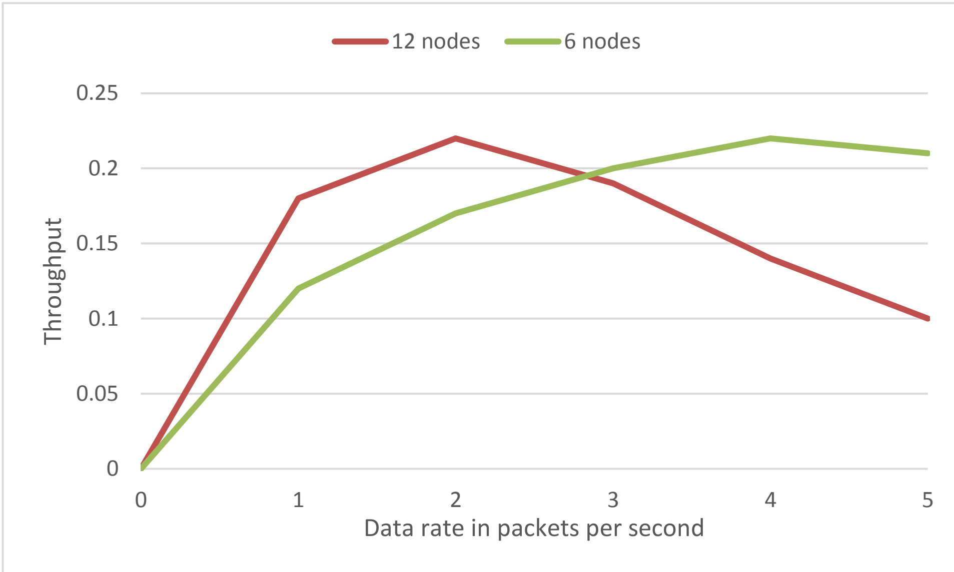


Figure 6.3: The throughput for a different number of nodes

6.4. Throughput and packets size of the network

In this simulation, it has been tested how different packet sizes affect ALOHA and ALOHA/CS throughput.

In Figure 6.4 ALOHA throughputs for 20 bytes packet and 120 bytes packet have been shown. For bigger packets, throughput reaches maximum quickly and then quickly decrease, this is due to increase the probability of collision. With larger packets, transmission time becomes bigger and probability that packets collide also become bigger. This is due to the design of protocol that sends data immediately and when transmission time increases, collision also increases.

Unlike ALOHA protocol, ALOHA/CS performs very differently with increasing size of packets. Figure 6.5 shows ALOHA/CS throughput for 20 bytes, 120 bytes, and 720 bytes packets. In this experiment, when packet size is increased, the throughput of the system is also increased. This improvement is possible because of carrier sensing mechanism. When we have large packets, the transmission time is bigger than the propagation time and, consequently, the utilization. Since ALOHA/CS will first sense the carrier, the probability of collision will decrease.

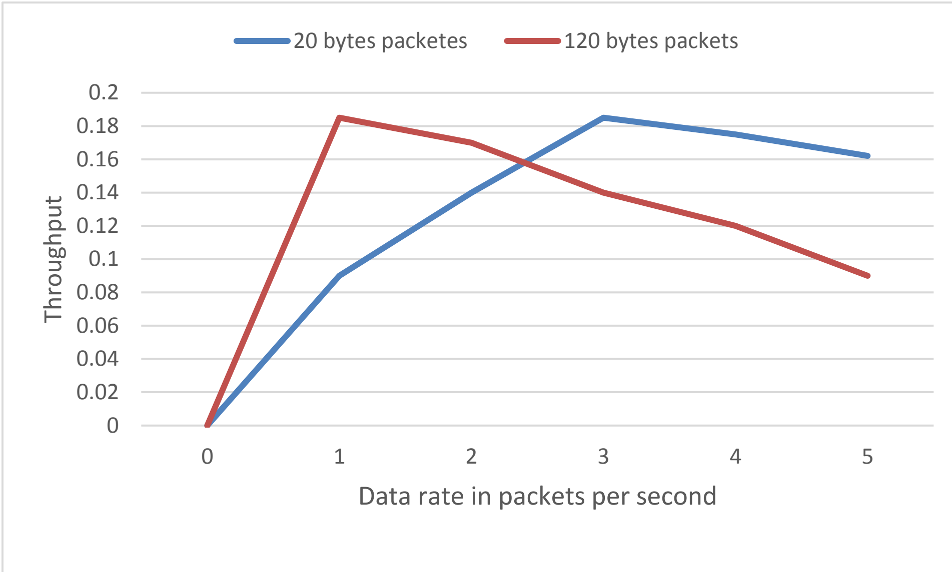


Figure 6.4: ALOHA throughput for a different size of packets

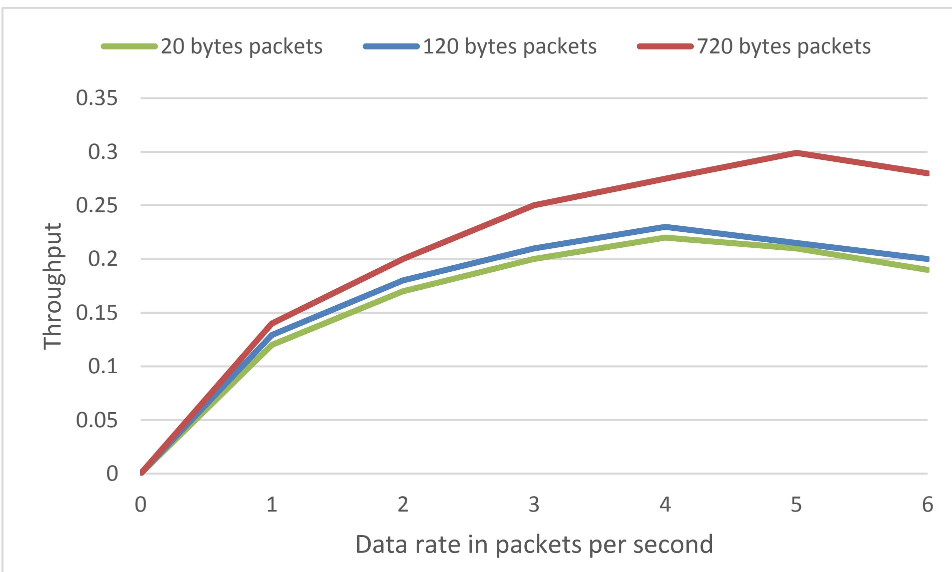


Figure 6.5: ALOHA/CS throughput for a different size of packets

7. Conclusion

7.1. Summary

This thesis offers a practical and straightforward solution for near real-time PIG tracking and pipeline pressure monitoring. The solution is a reliable, quick and cheap replacement for the existing system that uses ROV for information gathering from seabed sensors. The thesis proposes a simple architecture of the system that combined with reliable COTS equipment and appropriate protocols gives a highly reliable solution. The system is also very customizable and can be easily customized and adapted for other similar applications. Delay, throughput, and scalability of the system are tested with SUNSET simulation tool. Simulations show that the system satisfies the requirements, with an average delay of 7 seconds and the possibility of increasing the number of sensors without significant decreasing of the system's throughput.

7.2. Future work

7.2.1. Real-world testing

This work is mostly theoretical, and the real-world testing of the system needs to be performed. During simulations, it is assumed that there is no path loss and the packet loss can only be caused by collisions, and that is not true in real circumstances. Also, it is necessary to consider the influence of environment on buoy motions and their effects on surface communication.

7.2.2. Temporary connection loss

Temporary connection loss can significantly affect the delay in the underwater part of the network. The impact of this can be reduced using an algorithm that can find an alternative path for forwarding data to the sink node. In this case, the system will go from a single-hop to multi-hop communication.

7.2.3. Experiment with other protocols

TDMA media access protocol can be used as an alternative solution instead of ALOHA. TDMA will introduce more delay in the system, but the question is how it will influence the overall characteristics.

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