Low-Profile Floating Antennas for Coastal Communications

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This thesis is dedicated to my mother for her unconditional love and support.
Abstract

The size, orientation and features of an antenna are critically important in sea surface radio communications. The performance of the communication link is dependent on antenna height, radiation pattern and antenna-seawater interaction. This research focusses on the design and development of a short-range radio communication system with low-profile, low cost antennas that ensure reliable data transmission in a shallow seawater environment.

Given the high conductivity and relative permittivity of seawater, the system used the seawater as a conducting ground plane of infinite extent. This thesis reports the system challenges resulting from a non-planar sea surface and an imperfect ground conductivity. Given the high propagation loss through seawater at Ultra High Frequencies (UHF), the approach undertaken was a hybrid architecture consisting of a subsurface transmitter close to the ocean bottom (depth < 5 m) with a transmission line to the surface antenna, or a tethered but floating transmitter with an integrated antenna. Different techniques aimed at establishing communication links between the antenna and shore, another antenna and an Unmanned Air Vehicle (UAV) hovering above it, are reported. In all cases, the antenna moves laterally and rotates in all three axes with the wind and ocean currents, and vertically with waves and tides.

In the first technique, a communications link from a subsurface transmitter to a floating monopole antenna through an insulated wire surrounded by seawater was designed, constructed and tested. The attenuation is dependent on the wire and insulation thickness and this influences the characteristic impedance of the transmission line. A quarter wave monopole antenna was formed by placing the wire through a spherical polystyrene float with a length of approximately one quarter wavelength. The attenuation through the
insulated wire was approximately 38 dB/m. The vertically polarized radiation is omnidirectional in the plane of the water surface. Using a 10 dBm transmitter and a 1.5 m long subsurface transmission line, the maximum horizontal communications distance was less than 5 m between floating transceivers and up to 35 m to a slightly elevated shore receiver when the receiver sensitivity was -116 dBm. The packet loss for a 30 m separation between transceivers was 1.73%. When the insulated wire was replaced by a flexible coaxial cable, the transmission line attenuation and the propagation range across the surface to a slightly elevated receiver, extended to more than 140 m in light wind conditions.

The second technique was to use a floating transmitter with an integrated antenna. The antenna with the transceiver was located in a sealed 9 cm diameter Polyvinyl Chloride (PVC) pipe with a flexible rope tethered to the ocean floor. Two antenna designs were constructed and tested: a monopole and a modified spiral (hemispherical). The latter was assessed using a small conductive ground plane together with the sea surface. This antenna was optimized using Computer Simulation Technology (CST) and fabricated using 3D printing and vacuum forming. While the hemispherical antenna radiation beam is principally vertical, the horizontal propagation distance was measured as greater than 135 m for the receiver sensitivity of -116 dBm.

The final part of the research was the design and construction of a real-world prototype (floating buoy). Vacuum forming and 3D printing techniques were used to construct a waterproof enclosure to contain both the hemispherical antenna and the electronic circuitry. These techniques give a low-cost solution and the buoy can be modified to integrate ocean sensing elements. The buoy can be opened, and batteries can easily be replaced to increase the longevity of the transmitter. Due to the transparent structure of the buoy, the transceiver circuit could be partly powered with solar energy.
The longest transmission distance across the ocean surface was greater than 140 m using a low-profile hemispherical antenna integrated into the plastic enclosure containing the electronics given a transmitter power of +10 dBm and a receiver sensitivity of -116 dBm. The unit had a diameter of 20 cm and a height of less than 15 cm.
Declaration

I hereby declare that this work has not been previously submitted for a degree or diploma in any university. This thesis is my own work and contains no material previously published or work done in collaboration except where due reference is made in the thesis in itself.

Signed

Date: 31/10/2018

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Acknowledgement of Published Papers

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This thesis includes five published research articles co-authored with my supervisors. These papers contribute to Chapter 3, 4, 5 and 6 of the thesis. My involvement in each co-authored published article is detailed at the front of the Chapter. The details of the papers are:

Chapter 3:


Chapter 4:


Chapter 5:

Chapter 6:


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Abbreviations

ABS Acrylonitrile Butadiene Styrene

AUV Autonomous underwater vehicle

CST Computer Simulation Technology

EM Electromagnetic

PETG Polyethylene Terephthalate Glycol

PLA Polylactic acid

PVC Polyvinyl chloride

ROV Remotely operated vehicle

RSSI Relative signal strength indicator

UAV Unmanned Air Vehicle

WSN Wireless Sensor Network
Nomenclature

\( \sigma \) Conductivity

\( \varepsilon \) Permittivity

\( \alpha \) attenuation constant

\( \beta \) Phase constant

\( \gamma \) Propagation constant

\( d_{\text{LOS}} \) Line of sight path between transceivers

\( d_{\text{SR}} \) Ground reflected path

\( a \) Radius of the hemisphere

\( \omega \) Angular frequency

\( \eta_i \) Impedance of insulating material

\( k_L \) Complex wave number

\( Z_c \) Characteristics impedance

\( \tau \) Relaxation time

\( h_t \) Height of transmitter

\( h_r \) Height of receiver
Chapter 1

Introduction and Outline

1.1 Introduction

The coastal marine environment is vulnerable to the effects of human activity due to agricultural, industrial and urban development [Liu et al., 2008]. Ocean pollution has risen considerably over the last few decades resulting in degradation of water quality. Ocean monitoring is important for the understanding of water degradation, which allows measurements of water properties due to global warming and the rehabilitation of the ocean environment. Underwater wireless sensors can effectively detect and monitor seawater parameters in real time [Jiang et al., 2009]. Small wireless sensors in a dense array can easily be deployed and so they offer a low-cost solution to ocean monitoring.

In this project, we report the design and measurements of small radio transceivers nodes, which can communicate with each other, with the shore and with existing larger ocean buoys with large communication ranges. There are currently numerous ocean monitoring systems used to monitor ocean currents and water conditions. Acoustic communication has been so far the most reliable source of information gathering in seawater environment [Liu et al., 2008]. This includes monitoring aquatic ecosystems, oil extraction installations and detecting underwater earthquakes. Acoustic communication systems are mostly preferred for long distance underwater communication. In shallow waters, the technique suffers from multipath interference, link reliability and lower bandwidth (<100kHz) [Kilfoyle et al., 2007, Preisig et al., 2006]. Optical signals in seawater are limited by high absorption and scattering and they are not a good option in turbid waters [Kaushal et al., 2016]. Most of the optical systems use laser technology which requires
precise alignment between sensor nodes. This limits the use of optical systems to a fixed environment. Recently, radio communications have become a preferred choice for short distance communications since they are less affected by multipath interference and the turbidity of seawater. However, their use requires very low frequency and very high power. Using radio frequency (RF) signals, distances up to 100 m can be achieved provided the transmit power is approximately 45 dBm at a frequency range 1-20 MHz [Al Shammaa et al., 2004]. Moreover, RF communication through seawater at higher frequency (above 60 MHz) is deemed impossible due to higher conductivity of seawater [Al Shammaa et al., 2004].

Due to physical limitations of the current underwater communication technologies, there is a need to devise an alternative approach which makes it feasible to design RF systems for shallow coastal regions. The communication system needs to be low cost, smaller in size and most importantly, ensure reliable transmission of data. We have investigated the possibility that a higher radio frequency (433 MHz) can be used in a low-profile RF communication system which can operate at low power (10 dBm) and is well suited to shallow coastal areas with depths of less than 5 m. The seawater environment where the sea depth is limited to few meters is not suitable for acoustic and optical communication systems.

Due to the increased availability of Unmanned Air Vehicle (UAV), it is now easier to gather information from sensors located in a remote locality. In the ocean, this requires flying a UAV to communicate with a floating transceiver. One the most important features of an RF communication system is the antenna. The most popular choice is the use of monopole or dipole antennas for sea-land communication. The radiation of a vertically oriented monopole or dipole is directed horizontally along the seawater surface [Ulaby et al., 2007]. This type of antenna is less efficient for communications with an
elevated platform i.e. UAV or satellite. An antenna with radiation pattern directed in the vertical direction would be useful in information gathering when the transceiver is at significant distance from the base station.

The design and size of a floating transceiver antenna is a very important factor when it comes to sensor deployment close to coastal areas with significant tidal variations. The canal estates in Cleveland, Queensland, Australia, located at 27° 31' 0.09''S latitude and 153° 16' 16.24''E longitude have water channels with depth less than 5 m and width no more than 200 m [Brown et al. 2013]. Large buoys with elevated antenna are unsightly and interfere with local shipping. These environments are better suited for small sized buoys integrated with low-profile antennas floating on the sea surface.

1.2 Aim of the research

The aim of this research is to address the challenges of data communications in shallow seawater at higher MHz frequencies (ISM band 433 MHz). The goal was to design, construct and test communications systems which can transmit data from the seabed to the sea surface and from the surface to an onshore base station or to an elevated platform (UAV). Specific aims are as follow:

- Development of a hybrid architecture combining an insulated wire through water to the surface and radio communications at 433 MHz above water.
- Measurements of a flexible conducting cable (insulated wire and low loss coaxial cable) to transfer the radio signal from the seabed to the sea surface in shallow waters (~3 m).
- The design of two types of low-profile antennas: a monopole antenna for sea-land communications and a floating hemispherical antenna for communication with an
Introduction and Outline

... elevated platform. In this work, the propagation path from the sub-surface transmitter to an onshore receiver is also modelled.

- Development of low cost, small sized and waterproof prototypes (antenna floating buoys), using current manufacturing techniques such as 3D printing and vacuum forming.

1.3 Thesis outline

The thesis is composed by 7 Chapters, from which Chapters (3, 4, 5 and 6) are based on published papers with extra additional information.

Chapter 2 discusses the limitations of acoustic and optical communication systems in shallow water coastal regions. The benefits and challenges of a low-profile antenna systems for a particular environment are presented. The inter-dependence of seawater parameters (conductivity, permittivity, salinity and temperature) is explained with permittivity models using the Debye formulation. The effect of seawater conductivity and permittivity on the attenuation of RF signals is included as a literature review covering seawater measurements at MHz and GHz frequencies. The effect of wind speed and sea roughness on the communication link resulting in packet loss are presented. Antenna characteristics and frequency dependant attenuation of EM wave in seawater is considered. In addition, the theoretical attenuation of an insulated wire submerged in seawater (a coaxial cable equivalent) is outlined. The radiation characteristics of various floating antenna configurations are compared. Finally, 3D printing and vacuum forming techniques used to build a waterproof floating buoy housing the monopole and hemispherical antennas are presented.
Chapter 3 reports laboratory and field experiments performed with the hybrid architecture consisting of a monopole antenna fed by an insulated wire from the seabed. The attenuation of an RF signal from the seabed to the sea surface is reported both theoretically and experimentally. The propagation range was measured between two floating monopoles (sea surface communications) and between the monopole and an onshore base station (sea-land communications). The statistical analysis regarding the link reliability between transceivers as a result of wind speed and sea roughness was analysed. This work was published in *IEEE Journal on Oceanic Engineering* [Loni et al., 2017].

In Chapter 4, we further report the use of insulated wires for transferring RF data from the sea bed to sea surface. The signal attenuation for three insulated wires with different radii of insulation and inner conductor immersed in seawater was measured and compared with the theoretical formulation. Field experiments were conducted to determine the propagation range of these wires attached to a floating monopole antenna and compared with a low loss coaxial cable. Results were published in *Radioengineering* [Loni et al., 2018b].

In Chapter 5, a floating hemispherical antenna for ocean monitoring was investigated and compared to a floating monopole antenna. The experiments reported in this Chapter were conducted with the transmitter located close to the sea surface (i.e. no insulated wire feeding the antenna). The antennas were tested in the laboratory using a saline water bath, as well in the ocean to investigate the effect on the resonant frequency, return loss and bandwidth. Field experiments were performed in the ocean to measure the far field attenuation from both antennas. The antennas were assessed for horizontal propagation range although the principal radiation pattern for hemispherical antenna is in the vertical direction. The propagation model of the communication link was performed to calculate
the path loss between low height antennas. This work was published in *IEEE Journal on Oceanic Engineering* [Loni et al., 2018c].

In Chapter 6, the modelling and construction of a prototype (floating buoy) is presented. A waterproof arrangement was constructed using 3D printing and vacuum forming techniques. Simulations and laboratory experiments using the return loss measurements of vacuum formed hemispherical antenna are reported. The effect of seawater (an infinite ground plane) on the radiation pattern is discussed. This work has resulted in a conference paper published in *Antenna and Microwave Symposium (AMS)* [Loni et al., 2018a], and a journal publication in *Radioengineering* [Loni et al., 2018d].

The thesis concludes with a summary of the research findings. In particular, the use of the ocean as a conducting ground plane for both antennas. Further work in this field is suggested and outlined in Chapter 7.
Chapter 2
Literature Review

2.1 Introduction

This Chapter provides an overview of sound, light and radio waves for underwater communication between transceivers. A radio communication system with low-profile antennas communicating near to sea surface is outlined. The challenges in radio propagation due to antenna-seawater interaction are discussed. Due to lower antenna heights, the adverse effects of seawater conductivity and permittivity on radio wave propagation are defined. The change in wavelength, attenuation and intrinsic impedance of EM waves in a conductive medium are explained using simulated results.

In this Chapter, we discuss permittivity models to define the relation between different seawater parameters (conductivity, permittivity, temperature and salinity) [Klein et al., 1977]. These models have been used to find the permittivity of seawater using the Debye equation [Debye, 1945]. Moreover, the frequency dependent attenuation of an EM wave propagating in seawater is outlined. A mathematical formulation for an insulated wire submerged in seawater has been presented [King et al., 1981; Hartel et al., 2000], since it forms the basis for floating monopole antenna discussed in Chapter 3.

The Chapter includes a detailed literature review of EM wave propagation through seawater and across the sea surface. Moreover, it also discusses conventional buoy monitoring systems with elevated antennas. The use of different types of antennas for designing radio communication systems and the effect of sea roughness and wind speed on the communication link is also presented.
The Chapter concludes with a discussion on the mechanical design of a floating buoy. Vacuum forming and 3D printing techniques used for the fabrication of floating buoy are outlined. The changes in antenna characteristics due to seawater acting as an infinite ground plane are outlined. Based on this discussion, a radio communication system for shallow seawaters is proposed which consists of insulated wires and low-profile antennas floating close to sea surface.

### 2.2 Modes of Communication (seawater)

Sound, optical and radio waves can be used to communicate with ocean monitoring systems. Although acoustic systems are a preferred choice by some researchers, they have limitations in shallow water coastal monitoring. A brief explanation of the physical communication options is given in the following sub-sections.

#### 2.2.1 Acoustic communication

Acoustic communication for underwater data transfer is advantageous since it can travel over long distances as the absorption by seawater is relatively small (0.1- 4 dB/km Kaushal et al. [2016]). The main disadvantage is they are bandwidth and interference limited. Acoustics communication can offer bandwidth in the range of Hz which is quite small compared to RF communications. Three major factors affecting acoustic communication in the underwater environment are frequency dependent attenuation, multipath interference and data latency. Acoustic sensor deployment in shallow waters can result in reverberation which affects data rates and propagation distances. Also, acoustic communication is severely affected by noisy environments. There are several commercial modems available for underwater sensing, but their data rates are limited to kbps [Marine, 2018]. For short range communication, data rates up to 100 kbps are
achievable. Teledyne marine 900 series offer communication distances from 2 km to 6 km. Data rates can range from as low as 80 bps to 15 kbps depending upon the communication distance. Nowadays, underwater sensing requires a communication link which can support data communication in Mbps ensuring transmission of videos images over moderate distances.

2.2.2 Optical communication

The advantage of using optical communication for underwater sensing is the high data rate which can achieve data rates up to 1 Gbps. Latest commercial activity for optical device is Bluecomm 5000 which can offer a data rate up to 500 Mbps [Bluecomm, 2018] in a monitored environment. Optical sensors have limited use due to absorption at high frequencies as well as scattering due to suspended particles and air bubbles. In coastal communications, turbid seawater can result in data rate reduction and even the loss of the communications link. Moreover, optical sensors use photodiodes or laser technology for communication between sensor nodes. This requires alignment between sensor nodes for effective data transfer which increases the complexity of the system. Transceivers need to perform constant tracking of the radiation beam in the changing seawater environment. Due to this reason, optical sensors are mostly preferred for fixed point to point links [Kaushal et al., 2016].

2.2.3 Radio communication

Electromagnetic waves in the RF range are a preferred choice for short distance underwater communications since they provide high bandwidth and there is minimal data latency. The transmissions are not affected by seawater turbidity due to suspended particles and are effective for shallow water coastal monitoring. In addition, they have reduced system complexity because transceiver alignment is not required for efficient
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data transfer. The main issue with underwater RF communication is the high-power consumption which requires more than 30 W of transmit power for 100 m separation between transceivers at an operating frequency of 1-20 MHz [Al Shammaa et al., 2006]. The advantage of communicating at this frequency is we can achieve a data transmission rate in Mbps which is high enough to send video images. There are not many commercial modems working at radio frequencies however; a broadband RF modem S5510 offers a data rate of 1-10 Mbps up to a range of 1 m [WFS, 2009].

Table 2—1 Comparison of underwater communication technologies

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Acoustic</th>
<th>Optical</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation factors</td>
<td>Distance, frequency, Temperature, salinity and pressure</td>
<td>Distance, Absorption, scattering/turbidity, organic matter</td>
<td>Distance, frequency, Conductivity and permittivity</td>
</tr>
<tr>
<td>Data rate</td>
<td>kbps</td>
<td>Gbps</td>
<td>Mbps</td>
</tr>
<tr>
<td>Frequency band</td>
<td>$(10 – 15) \times 10^3$ Hz</td>
<td>$\approx 2.25 \times 10^8$ Hz</td>
<td>$\approx 2.25 \times 10^8$ Hz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>KHz</td>
<td>MHz</td>
<td>10-150MHz</td>
</tr>
<tr>
<td>Power (requirement)</td>
<td>Tens of Watts</td>
<td>Few watts</td>
<td>Few mW to hundreds of Watts</td>
</tr>
</tbody>
</table>

Table 2—1 summarises the pros and cons of the three communication technologies available for underwater communication. For long distance data transfer, acoustic communication is the best option, but it provides a low data rate and is not good for shallow waters due to increased multipath interference. Optical communication promises high data rate with low transmit power but in shallow waters it is severely affected by the turbidity of seawater and most importantly it requires complex transceiver tracking design. Radio communication offers a high data rate but requires very high power for
wireless transmission of data through seawater [Shaw et al., 2007]. From these discussions, we can conclude that radio communication is most suitable for shallow seawater environment if techniques are employed to reduce power requirements. This leads us to design a hybrid architecture comprising of guided media (insulated wire and coaxial cable) and unguided media which has less propagation losses so that the power required is milliwatts while transmitting data to considerably longer distance suitable for shallow seawaters with depth less than 5 m.

2.3 Coastal Radio Communication

Radio communication is advantageous in shallow seawater environments where the water depth is few meters (~3m). Design of a communication system is governed by the following factors;

a. The system needs to be cost effective. It also influences the density of an array of sensor nodes installed in an area. If the cost of each unit is too high, it may be too expensive to install a sufficient number of sensor nodes forming the network.

b. The communication system should be easy to install, to retrieve and to dismantle for maintenance purposes.

c. The material used in the design of a communication system must be such that does not adversely affect the marine environment.

d. Design and area coverage must be sufficient to effectively monitor the seawater volume of interest.

e. The nodes must be waterproof to protect the electronic circuitry from the harsh seawater environment.

f. The physical size of the transceiver (which includes the antenna) depends upon the need and scope of the coverage area under surveillance.
g. It is desirable that the transceivers must have the capability to partly meet its energy requirements utilizing environmental sources of energy such as sunlight.

h. Transceivers can easily be modified to accommodate more sensing devices.

i. Nodes must be tough and robust to withstand adverse climate changes in the seawater environment and their performance is not affected in rain.

The parameters discussed above provide guidelines to design an effective communication system. It must be noted that the development of a communication system for underwater sensing is entirely application driven and it may vary depending upon the size and needs of that particular environment. In next section, we discuss a shallow seawater environment which needs a low cost, small sized and reliable data communication system.

### 2.4 Operational Environment (Canal Estate)

Canal estate in Cleveland consists of small water channels with depth of approximately 3 m and width no more than 200 m. These canal systems are common in different parts of Australia (Figure 2—1). These artificial networks of waterways were created by excavating the land adjacent to the sea. The waterfront properties include boat mooring. Due to waterfront housing, sediments and pollutant flow into the sea degrading the water quality in these channels [Lemckert, 2006]. Lack of flushing and pollution results in a reduction of oxygen levels which threatens marine life. The drainage causes oxidation resulting in acid discharge which has adverse impact on vegetation and water quality [Cosser, 1989]. For that reason, it is of great interest to effectively monitor the quality of the water using real-time measurements of water properties including pH, salinity, pollutants, turbidity, temperature, and water speed and direction during rain and flood events.
Conventional radio communication systems for seawater environment use elevated RF modules where the transceiver antenna is placed at a height of 1.5 m or more above sea surface [Albaladejo et al., 2012; IMOS]. Further details regarding these RF systems is given in Section 2.8.2. This technique results in large sized buoys which are not suitable for some environments. Canal estates and similar environments need a radio communication system with low-profile antennas floating near the sea surface. This requires the size of the buoys to be small which can be deployed in small water channels so the interference with local shipping is minimal. For this purpose, we investigate the use of low cost, low profile unobtrusive antennas for short range wireless communication in shallow seawater environments.

The use of low-profile antennas brings a number of challenges for the communication link;

1. Reducing the height of antenna changes the propagation mechanism as communication is dependent on sea surface condition.

2. A low height antenna results in increased reflections angles which should be modelled to calculate the losses in a communication link.

3. Antenna-seawater interaction effects the performance of antenna.
(4) The orientation of the antenna becomes more important as the antenna gets close to the sea surface.

(5) The radiation pattern of the antenna changes due to the proximity of the seawater. It is important to understand radio wave propagation in this environment and to relate it to issues concerning the design of low-profile antennas for a short-range communication link. In the next sections, we report the effect of seawater on the characteristics of radio waves followed by radio wave measurements in diverse environments.

2.5 Radio waves propagation in a lossy medium

The propagation of EM waves through a medium depends on the conductivity and permittivity of the material [Ulaby, 2007]. The conductivity $\sigma$, is the ability of the body to conduct electric current. The conductivity of water depends on the temperature and salinity. TABLE 2—2 lists the approximate conductivity values of different water types [Rusydi, 2017].

The permittivity $\varepsilon$, is the ability of a material to store electrical energy in an electrical field and is written as $(\varepsilon_0 \varepsilon_r)$ where $\varepsilon_r$ is the relative permittivity and $\varepsilon_0$ is the permittivity of free space having value of 8.854 x $10^{-12}$ F/m. Most materials have relative permittivity values greater than 1 and water has one of the highest values of relative permittivity ($\varepsilon_r = 81$)[Klein et al., 1977]. The permittivity of material can be frequency dependant. The complex permittivity $\varepsilon_c$ for a conductive medium is written in terms of a real part $\varepsilon'$ and imaginary part $\varepsilon''$.

$$\varepsilon_c = \varepsilon - j\frac{\sigma}{\omega} = \varepsilon' - j\varepsilon'' \tag{2.1}$$

where $\varepsilon' = \varepsilon$ and $\varepsilon'' = \frac{\sigma}{\omega}$. For a lossless medium with $\sigma = 0$, it follows that $\varepsilon'' = 0$ and $\varepsilon_c = \varepsilon' = \varepsilon$. 
Table 2—2 Water types and approximate conductivity values [Rusydi, 2017]

<table>
<thead>
<tr>
<th>Types of Water</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.03x10⁻³- 0.05x10⁻³</td>
</tr>
<tr>
<td>Melted snow</td>
<td>0.2x10⁻³- 0.0042</td>
</tr>
<tr>
<td>Tap water</td>
<td>0.005-0.08</td>
</tr>
<tr>
<td>Fresh water stream</td>
<td>0.003-0.15</td>
</tr>
<tr>
<td>Industrial waste water</td>
<td>1</td>
</tr>
<tr>
<td>Seawater</td>
<td>5.5</td>
</tr>
</tbody>
</table>

The speed of an EM wave in a medium \((v)\) depends on permittivity \((\varepsilon_0)\) and permeability \((\mu_0)\) of the medium. In free space EM waves travel with the speed of light in a vacuum \((c_0 = 3 \times 10^8\text{ m/sec})\).

The speed of an EM wave in free space is given as:

\[
c_0 = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \tag{2.2}
\]

The wavelength \((\lambda)\) of an EM wave propagating in a medium with a frequency \((f)\) can be written as:

\[
\lambda = \frac{v}{f} = \frac{1}{f\sqrt{\mu_0\mu_r\varepsilon_0\varepsilon_r}} = \frac{c_0}{f\sqrt{\mu_r\varepsilon_r}} \tag{2.3}
\]

where \(\mu_r\) is the relative permeability and \(\varepsilon_r\) is the relative permittivity of the medium.

\[
\lambda = \frac{\lambda_0}{\sqrt{\mu_r\varepsilon_r}} \tag{2.4}
\]
\( \lambda_0 \) is the wavelength of EM wave in free space. Substituting the values (\( \varepsilon_r = 81 \) and \( \mu_r = 1 \)) in eq. (2.4) results in a nine times reduction in wavelength of radio wave for seawater environment.

### 2.5.1 Antenna characteristics

The antenna is a transducer which converts electrical energy from guided media to electromagnetic energy in non-guided media and vice versa. An antenna is characterized by its gain, efficiency and resonant frequency. The size of a self-resonant antenna depends on the operating frequency and reduces with increasing frequency and vice versa. Antenna efficiency is the ratio between the total radiated power and the input power. An ideal antenna converts all the input power into radiated energy. The antenna gain depends on the efficiency and directivity and gives information about the radiated power in one direction.

The radiation from the antenna is characterised in the near field \( (r < \frac{\lambda}{2\pi}) \) and far field \( (r > \frac{2D^2}{\lambda}) \) regions [Ulaby, 2007] where \( r \) is the distance from the centre of the antenna. Higher permittivity in close contact with the near field of an antenna affects its radiation characteristics. The result is a shift of the resonant frequency and a change in the radiation pattern. The conductivity of the propagation medium affects the attenuation of EM signals in the far field region and reduces the propagation range when the conductivity is high. The design parameters of an antenna operating in a conductive medium need further modification to achieve maximum impedance matching to a transmission link from the generator (usually 50 \( \Omega \)). The strength of the EM wave in the far field can be calculated using a link budget outlined by Friis [Ulaby, 2007] which is further explained in next section.
2.5.2 Path loss

The propagation distance achieved in a loss less medium communication link is calculated as a link budget which describes the relationship between the received power $P_r$ and the transmitted power $P_t$ as

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$ \hspace{1cm} (2.5)

where $P_t$ and $P_r$ represent the transmit and receive power. $G_t$ and $G_r$ are transmit and receive antenna gains and $d$ is the separation between two antennas.

EM waves from a small source propagating in free space are governed by the inverse square law, where power density ($P$) is proportional to the inverse of square of distance ($d$) from the source.

$$P \propto \frac{1}{d^2}$$ \hspace{1cm} (2.6)

2.5.3 Propagation constant

The attenuation of an EM wave in a medium can be calculated from the complex propagation constant ($\gamma$) [Ulaby, 2007].

$$\gamma = \alpha + j\beta$$ \hspace{1cm} (2.7)

where $\alpha$ is the attenuation coefficient and $\beta$ is the phase constant. $\alpha$ and $\beta$ can be written as:

$$\alpha = 2\pi f \sqrt{\frac{\mu \epsilon'}{2}} \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right) - 1}$$ \hspace{1cm} (2.8)
\[ \beta = 2\pi f \sqrt{\frac{\mu \varepsilon'}{2}} \sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1 \]

Thus \( \alpha \) and \( \beta \) depend on the complex permittivity and permeability of the material. For a point source, the electric field \( (E) \) at a distance \( (d) \) is given as;

\[ E(d) = E_0 e^{-\gamma d} \]

The attenuation coefficient \( \alpha \) is frequency \( (f) \) dependent and increases with increasing frequency. The ratio \( \left(\frac{\varepsilon''}{\varepsilon'}\right) \gg 1 \) defines seawater as good conductor for radio wave propagation. This only occurs at very low frequencies. Radio propagation at 1KHz with seawater conductivity of 4S/m results in \( \left(\frac{\varepsilon''}{\varepsilon'}\right) = 9 \times 10^5 \). The attenuation can also be calculated using equation \( \alpha \approx \sqrt{\pi f \mu \sigma} = 1.12 \text{ dB/m} \). For higher frequencies, eq. (2.8) is used because it is valid for any medium. The skin depth \( (\delta) \) is the penetration of an EM wave in a medium.

\[ \delta = \frac{1}{\alpha} \]

Skin depth at 1KHz is calculated as 0.89 m\(^{-1}\). Radio wave propagation at MHz and GHz frequencies results in further reduction of skin depth due to increased absorption.

### 2.6 Plane waves in seawater

The propagation of EM wave in seawater depends on permittivity and conductivity. The water can behave as a good conductor or insulator for radio waves and depends on the conductivity and operating frequency. The conductivity of seawater ranges between 4 to 7 S/m while the conductivity of fresh water is in the range \( 10^{-3} \) S/m. Due to lower
conductivity, fresh water behaves as an insulator for radio waves. The attenuation of a plane EM wave in fresh water is considerably lower compared to seawater. The magnetic permeability of seawater is 1, so has little effect. The permittivity of seawater is approximately equal to 81 which reduces the wavelength of radio waves in underwater environment. The attenuation of EM wave in a conductive media (seawater) is highly frequency dependent. At KHz frequencies, seawater can behave as good conductor however, higher frequencies undergo severe absorption which make it difficult to penetrate in conductive seawater and vice versa. The effects of seawater parameters on wavelength, attenuation and impedance of radio waves are given in the following subsections;

2.6.1 Wavelength

Figure 2—2 shows the change in wavelength ($\lambda$) of an EM wave for various frequencies and changes in the conductivity (0 to 1S/m). The wavelength $\lambda$ of an EM wave propagating in seawater is given by the approximation [Al Shammaa et al., 2004].

$$\lambda \approx 1.56 \frac{4}{\sqrt{\sigma f}}$$  \hspace{1cm} 2.12

where $f$ is the frequency and $\sigma$ is the conductivity in S/m.
Results show that higher frequency and conductivity significantly reduces the wavelength of radio waves.

### 2.6.2 Attenuation

Figure 2—3 shows the attenuation coefficient ($\alpha$) of EM waves in seawater. The complex permittivity and attenuation of an EM wave in seawater was calculated using eq. (2.1) and eq. (2.9).
Results show an attenuation of more than 150 dB/m at 433 MHz for a conductivity of 1 S/m. This makes it difficult to design RF systems for underwater wireless transmission of data where the average conductivity is around 5S/m.

2.6.3 Intrinsic Impedance

The intrinsic impedance of a medium $\eta$ is:

$$\eta = \frac{j\omega \mu}{\sqrt{\sigma + j\omega \varepsilon}}$$  \hspace{1cm} (2.13)

Impedance of free space is 377 $\Omega$. For pure water ($\varepsilon_r = 80, \sigma = 0$) at low frequencies having almost zero conductivity the value of impedance is $\eta = 42$ $\Omega$. The real and imaginary parts of the intrinsic impedance are plotted as a function of conductivity in Figure 2—4 and Figure 2—5 respectively.

![Figure 2—4 The complex impedance of seawater (Real) vs Conductivity ($\varepsilon_r = 80, \mu_r = 1$)](image-url)
Results show that at lower frequencies, the resistive component is close to 42 Ω and reactance is almost zero. The reactance increases with conductivity and frequency which results in more storage and less transmission of EM wave. At GHz frequencies, the resistive component can take the maximum value of 42 Ω.

### 2.7 Permittivity Models

As previously discussed, EM wave propagation through seawater is affected by permittivity and conductivity of seawater. Seawater properties (conductivity and permittivity) are dependent on temperature, salinity and frequency of propagation. The attenuation of an EM wave in a medium can only be calculated if we know the exact values of permittivity and conductivity for the given operating frequency. There are several permittivity models used to find the complex permittivity of seawater. These models are empirical formulas used to calculate the permittivity and conductivity of seawater as a function of seawater salinity, water temperature and operating frequency. All models are based on experimental data. These models give empirical formulas for each parameter in the Debye expression [1945].

![Figure 2—5 The complex impedance of seawater (Imag) vs Conductivity](image)
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\[ \varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} - j\frac{\sigma}{\omega\varepsilon_0} \]  \hspace{1cm} 2.14

where

\( \varepsilon_s \) is the permittivity value at static (zero) frequency. \( \varepsilon_\infty \) is the permittivity at infinite frequency. \( \tau \) is the relaxation time (the time taken by water molecules to return to their random distribution when oscillating electric field is removed) \( \sigma \) is the conductivity in S/m. Klein et al. [1977] proposed a permittivity model for calculating the complex permittivity of seawater. This is the most commonly used model for low frequency ranges (\( f < 10 \) GHz). The Klein-Swift model was used to find the seawater parameters since most of work in this thesis is centred at 433 MHz. In Chapters 3 and 4, the empirical modelling given by Klein-Swift (KS) model was applied to evaluate the complex permittivity of seawater which is further used to calculate the EM attenuation coefficient in conductive seawater.

The empirical formulas for the parameters (eq. 2.14) are given by Klein et al., [1977]. The value of \( \varepsilon_\infty \) is taken a constant i.e. 4.9.

- **Static permittivity (\( \varepsilon_s \))**

\[ \varepsilon_s(T,S) = \varepsilon_s(T)a(S,T) \]  \hspace{1cm} 2.15

where

\[ \varepsilon_s(T) = 87.134 - 1.949 \times 10^{-1}T - 1.276 \times 10^{-2}T^2 + 2.491 \times 10^{-4}T^3 \]  \hspace{1cm} 2.16

\[ a(S,T) = 1.000 + 1.613 \times 10^{-5}ST - 3.656 \times 10^{-3}S + 3.210 \times 10^{-5}S^2 - 4.232 \times 10^{-7}S^3 \]  \hspace{1cm} 2.17


• **Relaxation time (τ)**

\[
\tau(T, S) = \tau(T, 0)b(S, T) \quad 2.18
\]

\[
\tau(T, 0) = 1.768 \times 10^{-11} - 6.086 \times 10^{-13}T + 1.104 \times 10^{-14}T^2 - 8.111 \times 10^{-17}T^3 \quad 2.19
\]

\[
b(S, T) = 1.000 + 2.282 \times 10^{-5}ST - 7.638 \times 10^{-4}S - 7.760 \times 10^{-6}S^2 + 1.105 \times 10^{-8}S^3 \quad 2.20
\]

• **Conductivity (σ)**

\[
\sigma(T, S) = \sigma(25, S) \exp(-\Delta \beta) \quad 2.21
\]

\[
\Delta = 25 - T \quad 2.22
\]

\[
\beta = 2.033 \times 10^{-2} + 1.266 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2 - S(1.849 \times 10^{-5} - 2.551 \times 10^{-7}\Delta + 2.551 \times 10^{-8}\Delta^2) \quad 2.23
\]

and

\[
\sigma(25, S) = S(0.182521 - 1.46192 \times 10^{-3}S + 2.09324 \times 10^{-5}S^2 - 1.28205 \times 10^{-7}S^3) \quad 2.24
\]

Figure 2—6 shows simulated permittivity values with increasing frequency. These values are calculated for a fixed value of salinity (S = 30 ppt) and temperature (T = 24 °C).
2.8 Propagation mechanism

The attenuation of an EM wave in seawater depends on the propagation scenario and is different for propagation between transceivers through water or across the sea surface. Through-water propagation occurs between completely submerged sensors when the depth of submerged sensors is large enough to avoid surface wave propagation. Surface wave propagation between two floating sensors suffers considerably less loss when compared to through water propagation. If the propagation through seawater is guided e.g. an insulated wire, there is comparatively less attenuation. The attenuation in these propagation scenarios is frequency dependent.

2.8.1 Through water propagation

Figure 2—7 represents lateral wave propagation between transceivers submerged in shallow seawater. EM wave propagation in shallow waters can be through seawater, seabed or across the sea surface depending upon the operating frequency and depth of the
submerged sensors. Seawater has a conductivity of 5 S/m, and a dielectric constant of 81 which depends on the temperature and salinity [Klein et al. 1977]. When the conductivity of the seabed is 1 S/m, and air is assumed a lossless medium, at lower frequencies, the attenuation is a combination of through water and surface wave attenuation which are different in magnitude. At higher frequencies, the skin depth decreases, and the EM signals are completely absorbed by seawater before reaching the sea surface or seabed.

![Diagram of lateral wave propagation between submerged sensors](image)

**Figure 2—7** Lateral wave propagation between submerged sensors

Lloret et al., [2012] performed underwater experiments in a swimming pool using ISM band 2.45 GHz. Measurements were taken in a fresh water with temperature of 26°C and pH value of 7.2. Wireless connectivity between transceivers was achieved using an RF module based on 802.11 b/g standards with maximum power consumption of 460 mW. They achieved a data rate of 11 Mbps at 16 cm with less than 30% packet loss.

Rubino et al., [2015] investigated the transmission of a compressed image at 868 MHz in a pool filled with fresh water. The RF module operated at a maximum power of 25 mW and could achieve a data transmission rate of 64 kbps. Results show that they could send images up to 6 m in fresh waters.
Al Shammaa et al., [2004] performed propagation range experiments in seawater using the frequency range between 1 and 66 MHz. They used a dipole and loop antenna to carry out laboratory and open seawater experiments. He reported the effect of water conductivity on the near field and far field of the radiating antenna. Figure 2–8 shows the results of experiments conducted in a laboratory tank with transmit power of 10 dBm. The maximum propagation range was achieved by an antenna resonating at 25 MHz. Open seawater experiments were conducted at a Liverpool Dock. The transmitter power was stepped up to 4.75 W with resonant frequency set at 1 MHz. The results showed that a propagation range of 85 m could be achieved. The detector sensitivity is not mentioned in their results.

Lucas et al., [2007] also carried out experiments at lower MHz frequencies. He conducted experiments with 13 dBm transmit power using a loop antenna resonating at 25 MHz. He also investigated the attenuation of the EM fields in near field and far field of the antenna. His open seawater experiments resulted in a propagation range of 100 m with transmit power of 45 dBm. He concluded that frequencies from 1 to 10 MHz were most suitable for underwater radio propagation.

![Graph showing received power as a function of distance for through-water propagation](Al Shammaa et al. [2004])
Abou et al., [2012] performed underwater experiments at 433 MHz. They studied the propagation mechanism of different types of wire antenna in conductive seawater. Figure 2—9 represents the experiments conducted at 433 MHz with a transmit power of 0 dBm. Antennas were submerged in a fresh water tank with a conductivity of $\sigma = 0.013$ S/m. The best performance (minimum loss) was shown by $1\lambda$ loop, which only lost 9 dB for a propagation distance of 1m.

Shaw et al., [2006] investigated the use of loop antennas for underwater communication. They communicated a distance of 90 m with a transmit power of 5 W and claimed that data rate up to 500 kbps could be achieved at this frequency. The use of loop antenna brings directionally in the system design which needs alignment for good communication. For this reason, loop antennas are preferred for point-point link.

The analysis of these reported measurements taken over a wide range of frequencies with variable transmit power allow the following conclusions.
1) Underwater propagation through seawater is possible at lower MHz frequencies ranging from 1 to 25 MHz provided the transmit power is high.

2) ISM band (433 MHz, 2.45 MHz) can only propagate in controlled environment i.e. where the conductivity of water is very low (fresh water). Seawater with conductivity 5S/m results in higher attenuation and wireless transmission of RF data is not possible.

3) Monopole, dipole and loop antennas can be used for underwater propagation. Monopole and dipole have omni-directional radiation pattern however; loop antenna in the vertical plane become directional which increases the system complexity because transceivers need alignment for better communication. In horizontal plane, it shows omni-directional pattern but is not a popular configuration for loop antennas.

4) High data rates in Mbps are achievable at short distances with high transmit power.

This shows that underwater wireless transmission of RF data is not a viable option for designing a communication system at 433 MHz for shallow water coastal regions with depth less than 5 m. This leads us to investigate guided transmission (insulated wire and coaxial cable) through seawater and/or floating sensors above seawater.

### 2.8.2 Surface wave propagation

EM waves propagation across the sea surface is via surface wave propagation [Lee et al., 2012; Albaladejo et al., 2012]. The phenomenon can happen with floating sensors as well as submerged sensors. For submerged sensors, the depth of the submerged transceiver and wavelength of the EM wave are important. If the transmitter is operating at a very low frequency, then waves may reach the sea surface and travel across the surface and
reach the submerged receiver (lateral wave propagation). For floating sensors, the EM waves travel across sea surface and attenuation occurs due to both attenuations i.e. due to the conductivity value and scattering from the rough surface. Figure 2—10 shows the propagation scenario for surface wave propagation between floating sensors. Attenuation between sensors depends on several factors which includes the height of the transceivers, the distance and the sea state. The deployment of nodes in a sensor network is usually done close to ground which results in more losses as compared to other installed communication networks. Figure 2—10 shows the communication link between a floating transmitter and fixed onshore receiver. At short distances and an elevated transmitter, the LOS path is dominant which results in lower attenuation. Increasing the distance between transceivers results in higher attenuation due to surface reflection from the rough sea surface.

RF measurements exploiting surface wave propagation on oceans at MHz and GHz frequencies have also been reported.

Jackson et al. [2016] performed experiments at 2.45 GHz and achieved a propagation range of 35 m with transmit power of 0 dBm. They observed the propagation loss by placing transceivers at different heights above the seawater surface. The reported packet loss for 0.3 m elevation was 5.22% at 30 m.
Lee et al. [2012] investigated a microwave link (5.7 GHz) over seawater by placing antennas at variable altitudes of (0.37 to 0.91) Km. Most of their work was to observe the changes in received power (dB) due to the ducting effect for long distance communication over sea surface. They observed enhancement in dB levels due to ducting effect and performed empirical modelling to estimate the change by applying Gaussian and Rician distribution functions. Zhao et al. [2010] performed experiments at 8 GHz frequency and observed the effect of sea roughness and wind speed for long distance communication over sea surface. Figure 2—11 shows the extra loss in received power for a wind speed of 10 m/s. The received packet loss also increased from 1.2% to 8.7%.

![Figure 2—11 Effect of wind speed on signal propagation [Lee et al., 2012].](image)

This work reports radio wave propagation over sea water at different frequencies considering seawater parameters which include wind speed, sea roughness, height of transceivers. In addition to this work, there are several reported buoy monitoring systems designed for specific areas. These works emphasize on the buoy design, coverage area and RF technology used for communications.
The IMOS project being carried out by Australian Institute of Marine Sciences (AIMS) consists of large sized floating buoys used for underwater imaging of Great Barrier Reef (GBR). They created a network which consisted of relay poles installed every 2 km, communicating at 850MHz spread spectrum technology. The reported size of the two buoys was 1.8 m and 1.35 m (Figure 2—12). Data transmission used the 3G network and in case of remote stations, satellite communication was preferred.

Albaladejo et al. [2012] designed a buoy monitoring system for monitoring Mar menor coastal lagoon in the Mediterranean Sea. They used 2.45 GHz frequency with a transmit power of 17 dBm to design a monitoring system which can effectively transmit data over a distance of 1.6 Km with no packet loss. They used elevated structures to install the RF module and the antenna was placed almost 1.5 to 2 m above the sea level. The cost and weight of the buoy was €340 and 12 Kg respectively.

Based on the literature review discussed above one can draw the follow conclusions:

1) Data communication for floating sensors is affected by wind speed and roughness of seawater.
2) Surface wave propagation ensures long distance communication with elevated antennas.

3) The design of a monitoring system is governed by the need and type of information required from a given area of specific size, which also controls the density of sensor nodes.

4) With good design, high data rates in Mbps can be achieved with floating sensors with minimal packet loss.

2.8.3 Insulated wire transmission line

Underwater wireless communication is impossible due to the high attenuation offered by seawater conductivity. An insulated wire is a possible substitute for underwater applications and is already being used for submarine signalling. An insulated wire transmission line can be modelled as a coaxial cable with the inner conductor and the external medium (seawater) forming the lossy outer conductor. Transmission line formulae can be used to calculate the attenuation and the impedance of the insulated wire transmission line [Ulaby, 2007].

![Transmission line representation of an insulated transmission line](image)

Figure 2—13 Transmission line representation of an insulated transmission line [Milford, 2011]

Figure 2—13 represents a transmission line feed to an insulated monopole antenna terminated in load impedance $Z_L$ where $L$ represents the length of the lossy transmission
line, \( Z_0 \) is the characteristic impedance of the medium and the propagation coefficient is given by \( \gamma = \alpha + j\beta \).

Mismatching (\( Z_L \neq Z_0 \)) results in reflection of the transmitted power. The reflection coefficient \( \Gamma_L \) is given as

\[
\Gamma_L = \frac{Z_L - Z_c}{Z_L + Z_c}
\]

The input impedance \( Z_{in} \) to the transmission line with the load is given by

\[
Z_{in} = Z_0 \frac{Z_L + Z_c \tanh(yL)}{Z_0 + Z_L \tanh(yL)}
\]

and

\[
\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}
\]

where \( Z_0 \) is the characteristic impedance of the transmission line, \( Z_L \) shows the load impedance and \( \Gamma_{in} \) represents the input reflection coefficient of the lossy transmission line.

In Chapter 3 & 4, we use three insulated wires with different radii of insulation and inner conductor submerged in seawater feeding RF power to the floating monopole antenna. Their characteristic impedances were in the range 50 to 62.5\( \Omega \).

2.9 Hemispherical antenna

Ocean surface communications has been performed with monopole, dipole and loop antennas. A vertical monopole or dipole antenna has radiation pattern along the seawater surface which is useful for sea land communication. A loop antenna mounted in the vertical plane becomes a directional antenna which requires alignment for good
Literature Review

communication. For this reason, loop antennas are mostly preferred for point-point link. A hemispherical antenna has a vertically directed radiation pattern so is a good alternative for data collection from an elevated platform i.e. UAV. Moreover, this antenna structure offers high bandwidth and so a high data rate which is useful in high speed wireless telemetry systems [Alsawaha et al., 2010]. In addition, sea roughness and windspeed changes the orientation of antenna which results in a shift in resonance frequency. Due to the high bandwidth, the antenna maintains a low $S_{11}$ while floating on sea surface.

A spherical antenna is a modified form of a helical antenna introduced by Kraus [1948]. The geometry of the helical antenna is defined by three design parameters: diameter, height and spacing between the turns. The helical antenna can be modified by keeping one of the parameter constant and changing the other two [Kraus, 1948]. The spherical antenna is a special form of helical antenna where the spacing between the turns is constant (see Figure 2—14). The advantage of a spherical antenna over the helical antenna is the smaller electrical size. The radiation characteristics of a spherical antenna are independent of the number of turns however this cannot be reduced to the extent that the sphere loses shape. The truncated spherical antenna is the improvised form of spherical helix where the antenna is represented by the top or bottom half of the spherical antenna. This further improves the performance of the antenna with enhanced mechanical stability, improved bandwidth and axial ratio [Weeratumanoon et al., 2000]. Hemispherical antennas can show circular polarization over a broad angular range [Hui et al., 2003].
The antenna feed can be positioned on the side as well as from the centre of the sphere (see Figure 2—15). The centre fed antenna requires a wire link from the side to the centre of the hemisphere. This was first investigated by Chan, Hui and Yang [Clark, 2003]. The centre feed brings symmetry around the vertical axis which results in symmetry in the radiation pattern of the antenna. A side-fed antenna doesn’t require any additional wire however the radiation pattern becomes asymmetric. Also, the radiation characteristics are affected if the ground plane is not electrically large.

Figure 2—15 Centre fed (left) and side fed (Right) hemispherical antenna

Figure 2—16 shows the radiation patterns of a monopole and hemispherical antenna. A monopole antenna shows linearly polarization which can either be horizontal or vertical
Literature Review

depending upon the orientation of the antenna. For a vertical monopole antenna floating on water surface, the radiation pattern will be directed along the water surface. This radiation pattern is advantageous for sea-land communication. The pattern for a floating hemispherical antenna is directed in vertical direction (see Figure 2—16) and so is advantageous for data collection by an elevated platform (e.g. UAV, aircraft). This antenna shows high bandwidth which is good for high data rate communication.

Low profile antennas operating in seawater can undergo performance degradation depending upon their proximity to the seawater environment. The conductivity of seawater is much lower than copper which results in reduced antenna efficiency if used as a ground plane. The water permittivity results in a shift in the resonant frequency.

![Figure 2—16 Radiation pattern of monopole (left) and hemispherical antenna (Right) on a PED ground plane](image)

The design parameters of the antenna need modification to counter the seawater effects. For wire antennas, the insulation on a conducting wire is also effective in reducing the attenuation of an EM signal. As hemispherical antennas require a ground plane which is significantly large as compared to the radius of the hemisphere, at 433 MHz, the diameter of the copper ground plane should be 1.5 m which makes the size of the transceiver quite large. Seawater can be used as an infinite ground plane which is helpful in reducing the
size of the local ground plane. The performance of the antenna still deteriorates but it can be traded-off with the size of a copper ground plane. This effect is reported in Chapter 5 & 6 using floating hemispherical antennas with small sized copper ground planes floating on the sea surface.

2.10 Mechanical Design (Floating Buoy)

A sensor node consists of electronic circuitry and antenna which needs protection from the seawater environment. Recently, 3D printing has become very popular due to several advantages. Firstly, it provides design freedom and most structures can be printed in a relatively short time [Nkomo et al., 2017]. The cost of this manufacturing method is low which makes it one of the most preferred technologies for prototyping small-scale structures. The materials most commonly used for 3D printing are Acrylonitrile butadiene styrene (ABS) and Polylactic Acid (PLA).

PLA is biodegradable and built from organic material e.g. sugarcane or corn-starch. PLA material is structurally weaker compared to ABS and can’t withstand high temperature. ABS provides more rigid structures that can withstand relatively high temperatures and pressures.

Vacuum forming has been used to build plastic moulds for many years. The most common plastic material used for vacuum forming is called Polyethylene Terephthalate Glycol (PETG) [Nkomo et al., 2017]. The plastic sheet inside the vacuum forming machine is kept at an elevated temperature and low pressure. The temperature inside the vacuum forming machine may be varied depending on the material used for making plastic structures. Under low pressure it takes the shape of the mould under test and then upon cooling become a firm structure. This technology can be used to build water proof buoys which can contain the spherical antenna. The structures can be built at low cost since the plastic material used is not expensive and easily available. The vacuum formed structure
can isolate the antenna conducting elements from the seawater environment. The electrical properties of the plastic (conductivity and permittivity) do not significantly affect the radiation characteristics of the antenna. Permittivity and loss tangent of PETG at 1MHz are reported as 2.4 and 0.2, respectively.

2.11 Conclusion

Long distance underwater communication is usually performed with acoustic systems which offer lower data rates. Optical sensors are preferred in controlled environments and are not a good choice for shallow water monitoring because they suffer from turbidity which causes dispersion of light signals. Moreover, optical transceivers need alignment which complicates the design of a system. RF systems offer some advantages for shallow water monitoring but due to power limitations wireless data transfer is a problem. Most of the buoys designed for monitoring seawaters use elevated antennas installed almost 2 m above seawater surface. Coastal areas with congested water front housing having water channel with a width of 200 m need a communication system which consists of small sized buoys installed with low profile antennas. The system must be capable of transmitting data from the seabed to a base station located offshore or to a UAV. In next Chapters, we report the use of low-profile antennas for establishing a near to sea surface radio communication link. Propagation, orientation, radiation pattern and antenna-seawater interaction are investigated and comparisons between theoretical and experimental results are presented. Transceivers used in the experiments have fixed transmit power of 10 dBm and a receiver sensitivity of -116 dBm.
Publication:

Statement of contribution to co-authored published paper

The contents of **Chapter 3** were published in a peer-reviewed Journal. The bibliographic details of the paper are:


My contribution to the paper included antenna modelling, preparing setup for laboratory and field experiments, analysing theoretical and experimental results and drafting the paper.

Signed:  
Date: 26/10/2018

Zia M. Loni

Countersigned:  
Date: 26/10/2018

Hugo G. Espinosa

Countersigned:  
Date: 26/10/2018

David V. Thiel
Chapter 3
Hybrid Architecture for coastal communication

Low-cost tethered buoys are important for seawater observation, coastal area monitoring, and pollution sensing. Coastal communication at 433 MHz (ISM band) suffers high attenuation due to seawater conductivity. A significant propagation distance cannot be achieved through seawater or along the seabed. This work reports a novel technique for communication between transceivers operating in shallow water. A transmitter tethered to the bottom was connected to a floating monopole antenna via a flexible insulated wire transmission line. This configuration serves as a coaxial cable with the sea water forming the outer conductor. The wire must be flexible to accommodate changes in the tide and wave height variations. Experiments and calculations show that the attenuation along the transmission line was 38 dB/m. Surface propagation for buoy-to-base station was approximately 1 dB/m with a communication range of 30 m using a 10 dBm transmitter circuit with receiver sensitivity of −116 dBm. For buoy to buoy the surface propagation was measured as 3.5 dB/m with a communication range of 4 m. Experiments were carried out in calm water conditions. The results demonstrate that a low-profile insulated wire antenna can be used for coastal communication in shallow seawater environment providing the insulated wire in the water is reasonably short. This Chapter was published in IEEE Journal on Oceanic Engineering [Loni et al., 2017].

3.1 Introduction

Wireless transmission of radio waves through seawater is not possible at high frequencies with low transmit power. Chapter 2 gives detailed argument regarding
Hybrid Architecture for coastal communication

limitations of underwater radio propagation. In this Chapter, we present a novel technique for oceanic underwater communication between transceivers operating in shallow waters. A sensor tethered to the bottom was connected to a floating monopole antenna via an insulated wire transmission line for surface-based transmission. The transceiver were sealed in Polyvinyl chloride (PVC) and cemented in a plastic container. The protruding length of the wire attached to a Styrofoam buoy above the water surface was approximately one quarter of a wavelength (Figure 3—1). The radiation pattern of the vertical monopole antenna is along the seawater surface.

![Diagram of Floating monopole antenna with sensors enclosed in a PVC cylindrical pipe and cemented in a plastic container. The insulated wire passed through a Styrofoam float to form a Floating monopole above the sea surface with a quarter wavelength wire protruding the water.]

Before testing the proposed communication system, we performed experiments to measure the propagation range between submerged sensors for wireless transmission of RF data. Experiments were performed in laboratory and in open seawaters (Canal estate [Brown, 2007]). In laboratory, a water tank filled with saline solution having a conductivity of 0.2 S/m was used for testing transceivers. In open seawaters, the conductivity (σ) of seawater varied between 4 S/m and 6 S/m with a temperature range of 14ºC to 28ºC. The reported change in temperature and conductivity was measured over a period of one year. To estimate the propagation loss between two submerged
transceivers, we used permittivity models which are advantageous in calculating the relative permittivity of seawater. There are several permittivity models available however, we used Klein-Swift (KS) permittivity model since it is most suitable for frequencies less than 10 GHz [Klein et al., 1977]. Further details regarding the permittivity model and Debye formulation can be found out in Chapter 2. The attenuation between submerged sensors was calculated with Maxwell equations [Ulaby, 2007]. The results for wireless transmission were not good and the propagation range was limited to few centimetres.

After testing the transceivers for wireless transmission, we performed experiments with the proposed communication system which consisted of a guided transmission path (insulated wire) through seawater and wireless transmission across sea surface (Figure 3—1). Measurements were performed with the floating monopole and offshore fixed base station and between two floating monopoles. The attenuation from the submerged transceiver to offshore located base station can be divided into two parts; the submerged insulated wire which behave as a lossy coaxial cable with seawater acting as an outer conductor and wireless transmission between monopole and base station. The attenuation through the insulated wire was calculated using the theory for insulated wires in conductive media [King et al., 1981; Hertel et al., 2000]. The attenuation of EM waves in both propagation modes is dependent on the salinity, temperature and the operational frequency [O’Shaughnessy et al., 2012].

As discussed in Chapter 2, wind speed and sea roughness effect the propagation between floating transceivers. For this purpose, we tested our communication system by measuring the variation in dB levels and packet loss information. The link reliability for the proposed system was analyzed based on the measured results.
This Chapter is organized as follows. Section 3.2 describes the attenuation of EM waves propagating in two different media: between two submerged sensors for wireless data transmission, and through the insulated wire feeding the floating monopole antenna above the seawater surface. Section 3.3 discusses the measurement setup and the instrumentation equipment used for the experiments. Experimental results and data analysis are presented in Section 3.4. Finally, Section 3.5 concludes and summarizes the work.

### 3.2 Attenuation Model

A theoretical model was developed for two different situations: the attenuation of a plane wave through seawater at 433 MHz, and the transmission line impedance and attenuation in an insulated wire feeding the floating monopole antenna.

#### 3.2.1 Attenuation between submerged sensors

The attenuation of an EM wave propagating through seawater is calculated using Debye’s expression for the complex permittivity $\varepsilon_r$ [Debye, 1929], thus,

$$
\varepsilon_r(f) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i 2\pi f \tau} - i \frac{\sigma}{2\pi f \varepsilon_0},
$$

where $f$ is the frequency, $\sigma$ is the conductivity, $\varepsilon_s$ is the static permittivity, $\varepsilon_\infty$ is the permittivity at infinite frequency, $\tau$ is the relaxation time (the time taken by water molecules to return to their random distribution when the oscillating electric field is removed) and $i = \sqrt{-1}$.

The KS permittivity model was applied for frequencies $f < 10$ GHz. It gives empirical equations for the calculation of the Debye parameters as a function of seawater salinity.
Hybrid Architecture for coastal communication

and temperature. The value of $\epsilon_\infty$ is assumed to be a constant of 4.9 [Klein et al., 1977].

The complex permittivity obtained from (3.1) was used to calculate the attenuation of an EM wave propagating in seawater. The attenuation coefficient, $\alpha_{TH}$, for through water attenuation is given by [Ulaby, 2007],

$$\alpha_{TH} = 2\pi f \sqrt{\frac{\mu \epsilon'}{2} \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1}$$  \hspace{1cm} (3.2)

where $\epsilon'$ and $\epsilon''$ are the real and imaginary parts of the complex permittivity $\epsilon_r$ from (3.1).

TABLE 3—1 shows the attenuation of an EM wave using Debye expression and the KS model. The values of conductivity ($\sigma$) and temperature ($^\circ\text{C}$) in TABLE 3—1 were determined from laboratory and field experiments. The relaxation time ($\tau$) increases with decreasing salinity, so high salinity will result in an increased attenuation coefficient. The complex relative permittivity ($\epsilon_r$) values were calculated using Debye parameters for particular values of conductivity and temperature. The attenuation coefficient values ($\alpha_{TH}$) in TABLE 3—1 shows that the attenuation through water prohibits long distance propagation.

Table 3—1 The Electromagnetic parameters of seawater calculated using the Klein-Swift model [1977]

<table>
<thead>
<tr>
<th>Salinity (ppt)</th>
<th>Site</th>
<th>°C</th>
<th>$\sigma$ (S/m)</th>
<th>$\tau$ (ps)</th>
<th>$\epsilon_r$</th>
<th>$\alpha_{TH}$ (dB/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.30</td>
<td>Lab</td>
<td>15</td>
<td>0.2</td>
<td>10.50</td>
<td>81.75-10.11i</td>
<td>45</td>
</tr>
<tr>
<td>36</td>
<td>Coast</td>
<td>16</td>
<td>4.5</td>
<td>10.30</td>
<td>73.55-188.87i</td>
<td>643.40</td>
</tr>
<tr>
<td>38.4</td>
<td>Coast</td>
<td>19</td>
<td>5.1</td>
<td>9.43</td>
<td>72.01-213.30i</td>
<td>701.16</td>
</tr>
<tr>
<td>38.5</td>
<td>Coast</td>
<td>24</td>
<td>5.6</td>
<td>8.26</td>
<td>70.40-236.57i</td>
<td>753.06</td>
</tr>
</tbody>
</table>

Figure 3—2 shows underwater wave attenuation as a function of frequency (1-500 MHz) for different values of conductivity as described in TABLE 3—1. As it can be seen in Figure 3—2, at high conductivity the attenuation increases considerably and restricts
the wave propagation to longer distances. The proposed floating monopole antenna fed by an insulated wire overcomes this problem, as it exploits surface wave propagation for communication between two floating buoys and between buoy and an offshore base station.

Figure 3—2 Underwater wave attenuation ($\alpha_{TH}$) as a function of frequency for different conductivities.

### 3.2.2 Attenuation of the insulated wire

The propagation coefficient for an insulated wire transmission line with circular cross-section submerged in seawater is defined as [King et al., 1981; Hartel et al., 2000],

$$\gamma_{IW} = \alpha_{IW} + j\beta_{IW} = jk_L \quad (3.3)$$

where $\alpha_{IW}$ is the attenuation of EM wave in the insulated wire feeding the floating monopole and $\beta_{IW}$ is the phase constant. The subscript $w$ is used here to indicate the parameters that correspond to the insulated wire. The complex wave number $k_L$ is

$$k_L = k_i \sqrt{\frac{h_o + k_e b \ln(b/a) h_1}{(k_i/k_e)^2 h_o + k_e b \ln(b/a) h_1}} \quad (3.4)$$

Here, $a$ and $b$ are the radii of the conductor and insulation, respectively, $k_i$ and $k_e$ are the complex wavenumbers representing insulation and seawater which further depends on
the conductivity and permittivity of the materials and are defined as

\[
k_i = \omega \sqrt{\mu_0 \varepsilon_0} \frac{\varepsilon_{r\omega} - j \frac{\sigma}{\omega \varepsilon_0}}{\sqrt{1 - j \tan \delta}}
\]

(3.5)

\[
k_e = \omega \sqrt{\mu_0 \varepsilon_0 \varepsilon_{ri}} \sqrt{1 - j \tan \delta}
\]

(3.6)

where \(\tan \delta\) and \(\varepsilon_{ri}\) are the loss tangent and relative permittivity of the insulation, \(\varepsilon_{r\omega}\) and \(\sigma\) represent the relative permittivity and conductivity of seawater surrounding the insulated wire and \(\mu_0\) and \(\varepsilon_0\) are the free space magnetic permeability and electric permittivity, respectively. The angular frequency is \(\omega = 2\pi f\).

The characteristic impedance \(Z_c\) of the transmission line is given by

\[
Z_c = \frac{\eta_i}{2\pi} \frac{k_i}{k_i} \left( \ln(b/a) + \left( \frac{k_i}{k_e} \right)^2 \frac{1}{k_e b h_1} \right)
\]

(3.7)

where

\[
h_o = H_o^{(2)}(k_e b)
\]

\[
h_1 = H_1^{(2)}(k_e b)
\]

Here, \(H_n^{(2)}\) correspond to the Hankel functions of second kind. The impedance of the insulating material is given by

\[
\eta_i = \sqrt{\frac{\mu_0}{\varepsilon_{ri} \varepsilon_{ri}}} \quad \text{with} \quad \varepsilon_{ri} \quad \text{as the relative permittivity of the dielectric material.}
\]

TABLE 3—2 lists the PVC coated wire parameters used in these experiments, and Figure 3—3 shows the propagation loss calculated from (3.3) to (3.7) for a frequency range of 1-500 MHz.
TABLE 3—2 Insulated wire parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2a$ Conductor diameter</td>
<td>0.65 mm</td>
</tr>
<tr>
<td>$2b$ Insulation diameter</td>
<td>1.60 mm</td>
</tr>
<tr>
<td>$\epsilon_{r\omega}$ Seawater Permittivity (Debye)</td>
<td>69.40</td>
</tr>
<tr>
<td>$\sigma$ Seawater Conductivity (Debye)</td>
<td>6.1 S/m</td>
</tr>
<tr>
<td>$\epsilon_{ri}$ Insulation Permittivity</td>
<td>3.3</td>
</tr>
<tr>
<td>$\tan\delta$ Insulation loss tangent</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Figure 3—3 Propagation loss for an insulated wire in sea water.

The real part of the impedance in (3.7) was calculated for 57 Ω at 433 MHz using the parameters defined in TABLE 3—2, which indicates that some minor impedance matching is required to obtain maximum power from the insulated wire to the monopole antenna with impedance 35 Ω. This was achieved by a slight change in the length of the floating antenna above the water surface. At 433 MHz, the attenuation through the insulated wire was 38 dB/m. Thus, the EM attenuation through seawater (see TABLE 3—1) is much higher than the transmission line attenuation, but both are influenced by the temperature and salinity of the water. In addition, the attenuation depends significantly on the diameter of the conductor and the insulated material. Increasing the insulation diameter would result in a decreased attenuation through the insulated wire.
The use of an ISM band at 433 MHz provides more advantages when compared with other bands such as 6.7 MHz or 2.45 GHz. Figure 3—3 shows that the attenuation at 6.7 MHz is 0.45 dB/m, this would allow the insulated wire to extend to more than 100 m. However, the size of antenna (>10 meter) protruding the seawater surface would also increase considerably. There is, therefore, a compromise between the length of the insulated wire underwater and the length of the wire protruding the water surface. At 433 MHz, the system was suitable for ocean monitoring where the water depth ranges between 1.5 to 3 m. Note that a vertical monopole has a principal radiation direction along the water surface. Changes in orientation due to wave movement will vary the received signal strength.

3.3 Equipment and measurements setup

Several experiments were performed in a laboratory saline tank and in shallow, coastal seawater to determine the propagation range between two sensors operating at 433 MHz. The instrumentation and measurement setup are discussed as follows.

3.3.1 Wireless sensors

An identical pair of battery powered radio transceivers (433 MHz, +10 dBm) was used to communicate between them by detecting the relative received signal strength (RSSI). The units consisted of a ground plane comprising the circuit board electronics (60 mm × 40 mm) with a linearly polarized quarter wavelength monopole (whip antenna) of 173 mm (Figure 3—4). The frequency was adjusted in the range of 433 MHz to 454 MHz (ISM band). An on-board Micro SD card stores data up to 8 GB. Each unit can be used in continuous wave mode or as Master/slave for packet transmission at 1, 5 and 10 samples per second. The RSSI power level was recorded in dBm and the packet loss was...
logged. PVC pipes and sealed plastic bags were used to protect the units from direct contact with water. The units were used for both laboratory and seashore experiments.

Figure 3—4 Radio transceiver used to detect the received signal strength (RSSI) at 433 MHz.

3.3.2 Submerged sensor measurements

A rectangular glass container with dimensions $(90 \times 38 \times 45) \text{ cm}$ was used to determine the propagation distance of an EM wave at different conductivity levels, ranging from 0.2 S/m to 6 S/m during laboratory measurements [Aubry, 2015]. Sodium chloride was added to fresh water to control the conductivity using an LC81 conductivity meter from TPS Pty Ltd. The temperature was recorded using a Fluke IR Thermometer. PVC pipes with diameter of 90 mm and height of 330 mm were used to protect the units. The measurement setup is shown in Figure 3—5. The return loss measurements were undertaken using a vector network analyzer (N9923A).

Figure 3—5 Setup for laboratory measurements using a glass container filled with a saline solution. The transmitter circuit board and battery and the wire monopole were supported by a thin, semi-rigid Styrofoam sheet.

For the field experiments, the same PVC pipes were used to enclose the transceivers and were submerged close to the seashore at approximately 1 m depth.
3.3.3 Floating monopole measurements

The setup for the floating monopole antenna configuration is shown in Figure 3—1. The transceivers were enclosed in PVC pipes and cemented in plastic containers. Instead of the whip antenna used in the previous experiments, a 2.5 m, flexible insulated wire was extended from the submerged unit to a spherical Styrofoam float (diameter of 125 mm) with a quarter wavelength of the wire protruding above the water surface.

3.4 Results

The following experiments were conducted: communication between two submerged transceivers, communication between one submerged transceiver attached to a floating monopole antenna and an offshore transceiver, and surface communication between two submerged transceivers attached to floating monopole antennas. The results are compared with those obtained from the theoretical calculations described in Section 3.2.

3.4.1 Measurements between submerged sensors

Antennas operating underwater suffer from a shift in resonance frequency. To mitigate this shift, the antennas were tuned to operate at high frequency. TABLE 3—3 shows the shift in resonant frequency for the antenna tuned to 455 MHz and 540MHz in air, and the frequency shift when located inside the PVC pipe.

<table>
<thead>
<tr>
<th>ISM band</th>
<th>Frequency (MHz)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Above Water</td>
<td>Underwater (PVC pipe)</td>
</tr>
<tr>
<td>433 MHz</td>
<td>455</td>
<td>374</td>
</tr>
<tr>
<td></td>
<td>540</td>
<td>446</td>
</tr>
</tbody>
</table>

The EM attenuation of seawater was measured in the laboratory with the transmitter placed on the wall of the water tank while the receiver was submerged at the same depth.
The conductivity was set to 0.2 S/m and the receiver was gradually moved away from the transmitter with RSSI readings every 5 cm. Figure 3—6 shows the attenuation in dBm, which is linearly related to the distance (slope 86 dB/m), while the KS model was 45 dB/m for the same water conductivity.

The reasons for this high attenuation can be attributed to a number of uncertainties including the near-field antenna loss (the KS model is for plane wave attenuation), reflection loss at seawater–glass–air boundary and the meter used to measure the conductivity operates at 10 kHz.

Field experiments were mostly performed at Raby Bay canal estate, Cleveland, Redland City in southern Moreton Bay, Queensland, Australia, located at 27º 31' 0.09''S latitude and 153º 16' 16.24''E longitude with 4 m of elevation [Brown, 2013]. Some experiments were also performed at the Nerang River spit, Gold Coast, Queensland, Australia [Mogensen et al., 2014].

Attenuation levels are listed in TABLE 3—4, for different ocean conductivities and temperatures. The maximum separation distance between sensors was kept constant at 15 cm.
In laboratory and field experiments, the communication channel between transceivers achieved very short distances, with $< 1$ m for $\sigma = 0.2$ S/m and $< 15$ cm for $\sigma = 4.5$ S/m.

### 3.4.2 Measurements between floating buoy to offshore transceiver

The temperature and conductivity were measured as $28^\circ$C and $6.1$ S/m, respectively, and these values were used to calculate the attenuation in the insulated wire of the monopole antenna. Before the experiments were performed, a brief test was conducted to estimate the length of the insulated wire feeding the monopole antenna. The received power was measured offshore with a 2.9 GHz Field Strength Analyzer (Protek 3290 N) at a separation distance of 5 m. With the initial insulated wire of 2.5 m, the signal was not detected ($< -100$ dBm). The transmission line was shortened progressively until the signal was received. A 1.5 m long insulated wire received an average power of -94 dBm, the power level fluctuated with time as the small surface ripples changed the height and orientation of the floating monopole. When the insulated wire was reduced to 1 m, the received power observed at 5 m was -72 dBm. Further experiments were conducted with 1 m insulated wire feeding the monopole antenna.

The propagation range was measured using one unit submerged in water with a 1 m floating monopole and the other unit placed offshore acting as a base station. The measurements were performed at 5 m separation and gradually the floating buoy was moved away from the fixed base station to a distance of 40 m when no signal was received.
Figure 3—7 shows an approximate linear relationship between the received power and the separation distance. The slope of the line is approximately 1 dB/m. The variation in the received power was ± 2 dBm and the variation in separation distance was ± 1 m as the monopoles drifted due to the wind and waves. The measured results show the signal power dropping to -100 dBm at a distance of 35 m. The attenuation described in Section 3.2 predicted that a 1 m insulated wire surrounded by seawater feeding a monopole results in an attenuation of 38 dB.

\[
\text{Measured Data} = -0.81 \times m - 71, r^2 = 0.9467
\]

TABLE 3—5 shows the packet loss for buoy to base station communication. Packet data was collected at three different separation distances (10, 20 and 30 m). The packet frequency was 5 samples/second for all trials. No packets were lost for 10 m separation; however very small percentage of packet loss was recorded for 20 and 30 m separations. From the packet data, mean and standard deviations were calculated to determine the variations in dB level at each separation distance. The standard deviation shows that the variation in received power is less than 2 dBm for each separation distance.


TABLE 3—5 Percentage packet loss as a function of separation distance
Buoy to Base station

<table>
<thead>
<tr>
<th>Separation (m)</th>
<th>Percentage packet loss</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Packet loss (%)</td>
<td>Sample frequency(Hz)</td>
</tr>
<tr>
<td>10</td>
<td>0% (1284/1284)</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>0.62% (1276/1284)</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>1.73% (1019/1037)</td>
<td>5</td>
</tr>
</tbody>
</table>

3.4.3 Measurements between two floating buoys

The propagation range between two floating monopoles with a 1 m insulated wire was also measured using the procedure described in Section 3.4.2. Figure 3—8 shows the error bar for a buoy to buoy communication link. The slope of the line is 3.5 dB/m and a variation in the received power is 3 dBm. Results show that a propagation distance of approximately 4 m is achievable. From Section 3.2, the combined attenuation for two floating antennas is 76 dB. Most of the signal power is attenuated within the two insulated wires submerged in seawater which results in the reduced propagation range.

![Attenuation of EM wave (buoy to buoy) represented by error bars.](image)

Figure 3—8 Attenuation of EM wave (buoy to buoy) represented by error bars. The experiment was conducted at Cleveland (Brisbane) coastal area.

TABLE 3—6 shows the packet loss for a buoy to buoy link. Results show that there is almost 15 % packet loss up to 2 m separation between buoys. Beyond 2 m, the packet loss increased significantly and at 5 m there was almost 100 % packet loss. The standard
deviation of the measured data is included in the table. The results show a variation of approximately 3 dBm for up to 3 m separation between buoys. However, as the distance increases beyond 3 m, due to high packet loss, the standard deviation increases to 5 dBm.

<table>
<thead>
<tr>
<th>Separation (m)</th>
<th>Percentage packet loss</th>
<th>Sample frequency (Hz)</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.49% (997/1002)</td>
<td>5</td>
<td>-93.17</td>
<td>2.55</td>
</tr>
<tr>
<td>2</td>
<td>14.83% (867/1018)</td>
<td>5</td>
<td>-97.68</td>
<td>2.95</td>
</tr>
<tr>
<td>3</td>
<td>77.18% (298/1306)</td>
<td>5</td>
<td>-102.44</td>
<td>2.60</td>
</tr>
<tr>
<td>4</td>
<td>97.12% (37/1288)</td>
<td>5</td>
<td>-102.07</td>
<td>5.25</td>
</tr>
<tr>
<td>5</td>
<td>99.69% (4/1314)</td>
<td>5</td>
<td>-102.10</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3—9 shows the variation in the received power over a time period of 120 seconds. The floating buoy to base station power variations are given for 10 m separation while for buoy to buoy the variations are shown for 1 m. Results show that received power fluctuation over time for the buoy to buoy link is larger as compared to buoy to base station. These variations are the result of surface ripples and the changing monopole antenna orientation result in more packet loss for buoy to buoy communications. The link quality for buoy to base station is more reliable as compared to buoy to buoy communications.
communication. These variations also depend on the tide intensity. For high tides the variation increases and results in more packet loss [Jackson et al., 2015].

3.5 Conclusion

EM wave propagation at 433MHz below and above seawater surface was investigated through calculations and experiments. The floating monopole antenna proved successful at 30 m for sea surface to offshore communication with a 1.73% packet loss. For communication between floating buoys, a propagation distance of 4 m was achieved, with comparatively higher packet loss. This is usually sufficient as sea state parameters such as temperature, conductivity, pH, turbidity, water speed and direction, commonly change more slowly. Due to the high attenuation of an insulated wire in the ocean (38 dB/m), the length of wire was limited to 1 m. Coastal seawater monitoring is commonly reported at a distance of 1 m from the bottom of the water. The technique reported here is adequate for coastal zone investigations to a depth of 2 m. Further investigations are required for extending the length of insulated wire to 3 m, which is the average depth of a canal estate. Moreover, communication between floating buoys need further improvement in terms of propagation distance and link reliability. In order to measure the water quality of the canal estate, salinity, turbidity, temperature, pH and pressure sensors would be integrated into the transceiver, and together with a floating monopole antenna, the system could establish an economical WSN for coastal region investigations.
Publication:

Statement of contribution to co-authored published paper

The contents of Chapter 4 were published in a peer-reviewed Journal. The bibliographic details of the paper are:


My contribution to the paper included antenna modelling, preparing setup for laboratory and field experiments, analysing theoretical and experimental results and drafting the paper.

Signed: Zia M. Loni Date: 26th October 2018

Countersigned: Hugo G. Espinosa Date: 26/10/2018

Countersigned: David V. Thiel Date: 26th October 2018
Chapter 4

Further investigation into low-profile insulated wire antennas

The experimental and theoretical work covered in Chapter 3 was extended to explore the attenuation of the thin, flexible, insulated wire submerged in seawater. The attenuation at ultra-high frequency (UHF) is dependent on the operating frequency, the diameter of the insulating material and inner conductor. An extension of the insulated wire above the surface through a spherical float forms a monopole antenna. The effect of electromagnetic (EM) wave propagation at 433 MHz through insulated wires with different radii of the insulating material and inner conductor were investigated. The attenuation was calculated and measured in the range of 32-47 dB/m. The propagation from the monopole antenna to a fixed shore-based receiver was measured to be approximately equal to 1 dB/m. The propagation measurements were compared with a flexible commercially available 50 Ω shielded coaxial cable (RG 174/U). Results show that the propagation range depends on the ratio of the insulation radius to conductor radius for insulated wire, however, the shielded coaxial cable showed no significant attenuation. This Chapter was published in Radioengineering [Loni et al., 2018b].

4.1 Introduction

In Chapter 3, we successfully tested floating monopole antenna fed by an insulated wire transmission line. It was reported that attenuation through the insulated wire depends on radius of insulation and inner conductor, operating frequency and seawater parameters (conductivity and permittivity). The led us to further investigate the characteristics of an insulated wire and its dependence on the radius of insulation and inner conductor. For this
Further investigation into low-profile insulated wire antennas

purpose, three commonly available low-cost connecting wires with PVC insulation with different radii of the insulation and inner conductor were investigated. A complete configuration is shown in Figure 4—1 with a weighted plastic container holding an air-filled PVC pipe which contains the sensor node and transmitter circuit. Propagation range measurements were performed for each wire and attenuation through the insulated wire was calculated using methodology discussed by King and Smith [King et al., 1981; Hertel et al., 2000].

Figure 4—1 Floating monopole antenna above a tethered seawater sensor enclosed by a PVC cylindrical pipe and cemented in a plastic container. Wires (insulated and shielded coax) passed from the sensor through the water to a Styrofoam float to form a floating monopole above the sea surface.

In addition to the theoretical calculation, we also performed experiments in the laboratory to measure the reflection and transmission parameters of an insulated wire submerged in seawater. This would give us the measured loss through the insulated wire which can then be compared with theoretical formulation of King et al. [1981]. A plastic container filled with saline solution was used to test each wire for return loss measurements over a frequency range from 0 to 500 MHz. These results were also helpful for predicting attenuation at lower ISM band 6.7 MHz.
Further investigation into low-profile insulated wire antennas

We also assessed the use of coaxial cable for subsurface transmission of RF data. The shielded coaxial cable offers low loss (0.45 dB/m [Kuwes]) in underwater environment. An analysis between propagation range of insulated wires and coaxial cable was performed and advantages of low loss coaxial cable were also discussed.

We performed an experiment to see the effect of seawater conductivity and permittivity on the resonant frequency and return loss of a monopole antenna operating at 433 MHz. For this purpose, a quarter wavelength monopole was submerged in a water tank and conductivity was gradually increased from 0 to 4 S/m. The change in resonant frequency and return loss were reported. This procedure is helpful for tuning antennas in underwater environment.

In Chapter 3, we performed statistical analysis of the received power levels which gives information about the variations in RF data due to sea roughness and wind speed. In this Chapter, we do mapping of the raw packet data with gaussian distribution function as discussed for Lee et al., [2012].

Rest of the Chapter is organized as follows; Section 4.2 discusses the numerical modelling and simulated results for different insulated wire submerged in seawater. Section 4.3 reports the setup and results for laboratory and field measurements. Section 4.4 summarizes the work and provides recommendations for future implementations.

4.2 Methodology and numerical simulations

The attenuation through the insulated wire submerged in seawater has already been discussed in detail in previous Chapters. In this section, we only list formulas for calculating attenuation (α) and characteristic impedance (Zc).
Further investigation into low-profile insulated wire antennas

\[ \gamma = \alpha + j\beta = jk_L \]  

(4.1)

\[ k_L = k_i \frac{h_\alpha + k_e b \ln(b/a)h_1}{\sqrt{(k_i/k_e)^2h_\alpha + k_e b \ln(b/a)h_1}} \]  

(4.2)

\[ Z_c = \frac{\eta_i}{2\pi} \frac{k_L}{k_i} \left( \ln(b/a) + \left(\frac{k_i}{k_e}\right)^2 \frac{1}{k_e b h_1} \right) \]  

(4.3)

Table 4—1 lists the wire parameters, attenuation (\( \alpha \)) and characteristic impedance (\( Z_c \)), determined using equations (4.1) to (4.3), at 433 MHz for the three different copper wire configurations used in the experiments. The characteristic impedance is a complex quantity and results show that impedance is mostly real for all three wires.

Figure 4—2 shows the attenuation and Figure 4—3 shows the real values of the characteristic impedance as a function of frequency ranging from 1 to 500 MHz for the three wires (see Table 4—1). Results show that the attenuation in the insulated wire increases considerably with increasing frequency.

<table>
<thead>
<tr>
<th>Name</th>
<th>Conductor radius ((a)) (mm)</th>
<th>Insulation radius ((b)) (mm)</th>
<th>((b/a))</th>
<th>(f = 433) MHz</th>
<th>(\alpha) (dB/m)</th>
<th>(Z_c) ((\Omega))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire 1 (W1)</td>
<td>0.45</td>
<td>1.3</td>
<td>2.88</td>
<td>-32</td>
<td>62.5 - j 7.5</td>
<td></td>
</tr>
<tr>
<td>Wire 2 (W2)</td>
<td>0.3</td>
<td>0.75</td>
<td>2.5</td>
<td>-35</td>
<td>61 - j 7</td>
<td></td>
</tr>
<tr>
<td>Wire 3 (W3)</td>
<td>0.2</td>
<td>0.35</td>
<td>1.75</td>
<td>-47</td>
<td>50 - j 5.5</td>
<td></td>
</tr>
</tbody>
</table>
Further investigation into low-profile insulated wire antennas

Figure 4—2 Simulated attenuation coefficient $\alpha$ as a function of frequency, ranging from 1 to 500 MHz for the three different types of wires listed in Table 4—1.

The simulated results from Figures 4—2 and 4—3 were determined using the measured conductivity and temperature of seawater (6.45 S/m and 19 °C, respectively). These values were used to determine the permittivity of seawater using the Debye relaxation formulation [Debye, 1945; Klein et al., 1977]. The factor $(b/a)$ is the ratio between the radii of the insulation and the inner conductor. This factor is a major contribution to the attenuation of the insulated wire in seawater (see Table 4—1). Wires 1 and 2 have a different cross-sectional area but their ratio $(b/a)$ is approximately the same. The difference in the attenuation coefficient of both wires is very small. The ratio $(b/a)$ for wire 3 is the lowest and it results in the highest attenuation. This shows that the higher the value of $(b/a)$, the lower the attenuation of the EM signal through the insulated wire.

The characteristic impedance of Wire 3 is close to 50 Ω over most of the frequency range. However, wire 1 and wire 2 show a slight mismatch which results in a small reflection of power between the insulated wire and the monopole antenna. Moreover, the movement of the float changes the length and orientation of the monopole antenna even under light wind and wave conditions. Impedance matching was performed by adjusting the length of the monopole antenna above seawater surface.
Further investigation into low-profile insulated wire antennas

Figure 4—3 Simulated characteristic impedance \( Z_c \) (Real) as a function of frequency, ranging from 1 to 500 MHz for the three different wires listed in Table 4—1.

The relationship between seawater parameters is given by permittivity models. The values of salinity and temperature affect the electrical parameters of seawater which includes conductivity and permittivity. Figure 4—4 shows the effect of temperature change on the attenuation of EM wave at 433 MHz for different values of salinity. The values have been calculated using the empirical formulations given by Klein-Swift model [Klein et al., 1977]. The results show that the attenuation increases with temperature for a particular value of salinity.

Figure 4—4 Attenuation as function of temperature at 433 MHz for selected values of salinity (S in ppt). The temperature range is from 19 °C to 28 °C.
4.3 Measurements

Measurements were carried out in the laboratory to determine EM wave attenuation through a submerged insulated wire. In addition, a test was conducted to verify the effect of seawater conductivity on the resonance shift of a quarter wavelength monopole antenna. Moreover, field tests were performed to determine the propagation range of a floating monopole antenna fed by a submerged insulated wire. A comparison was also performed between three wires (see Table 4—1) and a shielded coax cable.

4.3.1 Laboratory Measurements

A rectangular plastic container was used for measuring the attenuation through insulated wires submerged in saline water in the laboratory (see Figure 4—5). A wire 72 cm long was positioned in the centre of the plastic container (72 cm × 36 cm × 15 cm). The insulated wire was connected to the centre of a circular copper ground plane with diameter of 12 cm on either side of the plastic container through an SMA connector. Measurements were performed using a portable Vector Network Analyzer [N9923]. The saline solution was prepared from sodium chloride mixed with tap water (20 gms/ltr). A conductivity meter (WP 81 from TPS Pty Ltd) was used to monitor the conductivity, and salt was added step-wise until the conductivity reached a level of 5 S/m. The ground plane was attached on the outer side of the container and had no contact with the saline solution. The setup for the saline water container represents a two-port network which was used to measure the transmission and reflection coefficients for the three insulated wires with different radii of insulation and inner conductor.
Scattering parameters for various wire configurations were measured 10 cm beneath the water surface. The reflection ($S_{11}$) and transmission ($S_{21}$) coefficients were measured over the frequency range of 1 to 500 MHz. The same parameters were measured in air. Figure 4—6 shows the return loss measurements for the three insulated wires. Measurements were performed with one end of the insulated wire connected to the VNA and the second end terminated with a matched load. The procedure was repeated for each wire.

All results show a resonant condition ($S_{11}$ minimum) at 28 MHz where the effective length of the wire is one quarter wavelength in the saline water. The wavelength in the saline container was calculated to be 10.34 m. Since the wire length is 72 cm, the relative permittivity of the saline water was $\varepsilon_r = 58.52$. The previous values of relative permittivity of seawater ranges between 72 to 80 [Klein et al., 1977]. This difference can be attributed to impedance mismatches during the measurements.
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The $S_{11}$ results show that wire 1 with the highest $(b/a)$ value has the lowest loss over most of the frequency range. In addition, the three insulated wires have almost the same resonant frequency. However, there is an offset in dB level for each wire. The dB offset between wire 1 and wire 2 is small since their $(b/a)$ ratio have similar values. Wire 3 shows the maximum loss due to the lowest $(b/a)$. These results show that the reflection depends significantly on the radius of insulation and the inner conductor. The frequency response of wire 3 shows minimal ripples since it is best matched to $50 \, \Omega$ (see Figure 4—6). Since the length of the wire is 72 cm, the attenuation $(\alpha)$ was calculated as 32 dB/m. The attenuation rate ($e^{-\alpha z}$) of the EM signal propagating in the saline container is given as $(E_1/E_0 = 0.025)$. From these results we can conclude that the dielectric constant $(\varepsilon' / \varepsilon'' >> 100)$ and the saline water behaves as a good conducting medium.

Figure 4—7 shows the transmission coefficient for the three insulated wires. Wires 1, 2 and 3 show a loss of 25.4 dB, 26.7 dB and 31.6 dB, respectively, at 433 MHz. As the length of the wire is 72 cm, these results can be recalculated in dB/m which matches closely the attenuation calculated in Section 4.2. The linear regression fit for the three wires shows a similar slope as the one from Figure 4—2 ($r^2 > 0.96$). The small difference in the calculated and measured attenuation rates are due to the difference in conductivity...
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and temperature of water which affects the attenuation in the insulated wire. The conductivity in the saline container was 5 S/m compared to 6.5 S/m measured in the ocean. The reverse transmission ($S_{12}$) and reflection ($S_{22}$) parameters were also measured, however; the results are not reported since they are indistinguishable.

The results reported above show that the power in an insulated wire submerged in seawater attenuates significantly with slight changes in length and diameter of the wire. The conductivity and temperature of seawater affect the signal power for the submerged wire. These results are not significant if the same wire is in air or sand due to the low permittivity and conductivity values as compared to water.

![Transmission coefficient ($S_{21}$) for the three insulated wires (W1, W2 and W3).](image)

The quarter wavelength in free space at 433 MHz is 17 cm. However, the seawater permittivity ($\epsilon_r = 80$) results in a shift of resonant frequency. This requires the antenna to be designed at a slightly higher frequency. The resonant shift due to the permittivity results in an antenna operating at required frequency i.e. 433MHz. Figure 4—8 further explains the effect of seawater permittivity on the resonant frequency. The monopole antenna was partially submerged in seawater and the conductivity of seawater was gradually increased from 1 to 4 S/m. Figure 4—8 shows the effect of seawater parameters on the antenna. The resonant frequency in air was recorded as 546
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MHz. When the antenna was placed over the water surface with a conductivity of 1 S/m, the frequency shifted due to the high permittivity of seawater and resonated at 446 MHz with a return loss of 17.66 dB. When the conductivity was gradually increased to 4 S/m, the return loss changed significantly and a slight change in the resonant frequency was observed. According to Klein-swift permittivity model, increasing the conductivity results in a partial change in permittivity ranging from 72 to 80. Moreover, the resonant shift also depends on the operating frequency and is less significant at higher frequency bands [James et al., 2010].

![Figure 4—8 The effect of seawater conductivity on the antenna resonant frequency measured as return loss.](image)

4.3.2 Field Measurements

Propagation measurements across the water surface from a floating buoy were performed at a canal estate in Cleveland, Queensland, Australia [Loni et al., 2017; Brown, 2013], where the water depth was between 1.5 to 3 m. The transmitter node (Figure 4—9) consists of a ground plane comprising the circuit board electronics (60 mm × 40 mm).

This was connected to the insulated wires and the received power was measured with a stationary spectrum analyzer located 1 m above the water surface [Proteck 3290N]. For comparison, a shielded coaxial cable was included in the measurements, the insulation
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around the protruding above water floating monopole was removed and measurements were performed with the bare inner conductor. Figure 4—10 shows the set up for the propagation range measurements, where $d_{LOS}$ and $d_{sr}$ correspond to the line-of-sight and surface reflected distance between the antenna and the receiver, respectively. Here $h_r$ is the height of the receiver above the seawater level, and $d$ is the horizontal distance between the antenna and the seashore.

![Radio transceiver](image)

Figure 4—9 Radio transceiver used for propagation range measurements operating at 433 MHz.

The sensor was submerged in seawater with the monopole (12.5 cm) floating above the sea surface. The first measurement was performed with wire 1 at a separation distance of 5 m from the receiver (Figure 4—11). The signal strength was -77 dBm.

The floating monopole was moved away from the receiver step-wise until the signal level dropped below -100 dBm. The same procedure was repeated for wires 2 and 3. For wire 2, the signal level dropped to -100 dBm at a separation distance of 25 m. For wire 3, the signal attenuation was much higher and it dropped at 15 m. The attenuation of an EM signal in seawater depends on a number of factors which includes sea roughness, height of the transmitter and the receiver, wind and water direction, and most importantly the operating frequency. The attenuation trends and variation in dB levels due to volatile seawater environment can be best explained by an empirical modelling. The empirical modelling includes curve fitting the measured data to track the decrease in power with distance. Moreover, the mean and standard deviation of the received power is calculated
Further investigation into low-profile insulated wire antennas to study the fluctuation in the received power. The linear regression lines were fitted to each measurement (see Figure 4—11). The slope of the line for each test is almost 1 dB/m for the surface propagation; however, there is a significant difference between the propagation ranges. The attenuation through wire 1 was the smallest (see TABLE 4—1), which results in more power at the floating monopole antenna. The attenuation through wire 2 is greater, and this results in a lower propagation range. Attenuation through wire 3 was the highest due to the lower ratio \((b/a)\), which resulted in the shortest propagation range.

![Figure 4—10 Set up for propagation range measurements. The height of the transmitter is equal to the radius of the hemisphere, and the spectrum analyzer is placed onshore on a rock wall at 1 m above seawater level.](image)

This procedure was followed for the propagation range measurements using the shielded coaxial cable. The results show that the signal level dropped to a maximum of -92 dB at a distance of 135 m which was almost the total width of canal estate. This shows that the shielded coax cable can transmit signal from the sea bed to the sea surface without any attenuation in signal power. A simple monopole antenna can be used to transmit the signal to an onshore base station resulting in increased propagation range.
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Figure 4—11 Attenuation between a floating buoy (Coaxial cable, Wire1, Wire2, Wire3) and base station on the shore. The measurements were made under light wind and wave conditions. The error bars show the RMS uncertainty in the measurements.

The vertical error bars in Figure 4—11 show the variation of ±3 dB which reflects the standard variation of the packet data. This variation was calculated using the packet data collected during the measurements. The statistical analysis of the packet data was developed as the one reported by Lee et al. [2012]. Figure 4—12 shows the histogram of the raw packet data collected during the experimental measurements, together with a mapping of the raw data using a Gaussian distribution function. The mean ($\mu$) and standard deviation ($\sigma$) for the packet data collected at a separation distance of 30 m was -98.05 dB and 3 dB, respectively. These values were used to plot the probability density function (PDF) that best fits the raw data. Furthermore, the packet loss was calculated as 1.73% for a separation distance of 30m between transceivers. These experiments were performed in light wind condition. The statistics reported above are valid for the sea state on the measurement day. A change in sea roughness would change the mean and standard deviation of the received power. Zhou et al. [2010] reported a packet loss of 1.2% for smooth sea surface (wind speed 0 m/sec), however, the packet loss increased to 8.7% for a wind speed of 10 m/sec. This shows that wind speed has a considerable effect on link quality of a communication channel in the seawater environment. The results reported in Figure 4—11 are for a floating sensor and a fixed onshore receiver. For a communication
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link between two floating sensors these statistics would further change and the link quality would deteriorate. Further analysis regarding link quality and packet loss between two floating buoys can be found in [Jackson et al., 2015; Loni et al., 2017]. Zhao et al. [2010] and Lee et al. [2012] performed experiments at GHz, which resulted in more losses. EM wave attenuation is frequency dependent and higher frequencies propagating over water surface would attenuate more as compared to lower frequencies. Moreover, an increase in antenna height results in reduced losses and vice versa.

![Figure 4—12 Best fitted PDF with the experimental data having mean ($\mu = -98$ dB) and standard deviation ($\sigma = 3$ dB).](image)

Seawater communication is affected by several factors and a compromise between transmit power, operating frequency, antenna height and sea roughness is required for a good communication link. The proposed work is beneficial for shallow water coastal monitoring where considerable propagation range can be achieved at 433MHz.

### 4.4 Conclusions

The characteristics of an insulated wire submerged in sea water at 433 MHz showed that the attenuation depends on the ratio of the radii of insulation and inner conductor for a particular frequency and the sea state conditions. The surface propagation range was 30
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m. This distance can be extended by changing the wire cross-section and increasing the transmitter power. The length of insulated wire can also be extended to approximately 2m before the link becomes unreliable. There is a compromise, however, between the length of insulated wire and the surface propagation distance. Increasing the length of the insulated wire reduces the surface propagation range for a fixed transmitter power output. Floating monopoles can be effectively used for shallow water coastal monitoring since they are low cost, low power and have a considerable propagation range that depends upon the operating frequency. The shielded coaxial cable shows almost no loss when immersed in seawater and so the surface propagation extends to much longer distances across the surface. The low cost, insulated wire solution is simple to deploy and would be suitable for closely spaced sensor nodes. For much larger distance and deeper sensors, the coaxial solution is preferable.
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Statement of contribution to co-authored publication

The contents of Chapter 5 were published in a peer-reviewed Journal. The bibliographic details of the paper are:


My contribution to the paper included antenna modelling, preparing setup for laboratory and field experiments, analysing theoretical and experimental results and drafting the paper.

Signed: Zia M. Loni  
Date: 26th October 2018

Countersigned:  
Date: 26/10/2018

Hugo G. Espinosa

Countersigned:  
Date: 26th October 2018

David V. Thiel
Chapter 5
Low-Profile Floating Hemispherical Antenna

This Chapter reports an investigation into the effectiveness of a floating transceiver without an electrical connection to the ocean floor. Monopole (see Chapter 4) and loop antennas have been used in seawater; however, a hemispherical antenna has the advantage of an increased efficiency and propagation range compared to other designs. The design, construction, testing and simulation of a hemispherical antenna and its propagation across the sea surface is reported. The principal radiation pattern of a hemispherical antenna is in the vertical direction to the sea surface. Antenna modelling shows a return loss of -15 dB and a radiation efficiency of 57% in a partially submerged condition. The modelled and measured bandwidths were 47% and 36%, respectively. Propagation range measurements in a calm coastal bay showed two separate attenuation trends of 2 dB/m and 4 dB/m, before and after the reference distance (40 m), respectively. The link range was greater than 135 m using a transmit power of 10 dBm and a receiver sensitivity of -116 dBm. Results show that the floating hemispherical antenna can be successfully deployed and used in wireless sensor network applications for coastal areas. This work was published in IEEE Journal on Oceanic Engineering [Loni et al., 2018c].

5.1 Introduction

Previous work (Chapter 3 & 4) focusses on the use of conductive cable (insulated wire or low loss coaxial cable) from a transmitter placed at sea bed. This architecture is useful for information sensing from sea bottom (depth < 5 m). A monopole antenna has an
omnidirectional radiation pattern along the surface of seawater which is useful for seashore communication. We investigate the use of a low-profile hemispherical antenna resonating at 433 MHz for shallow water coastal communication and compare it with the performance of a monopole antenna. Unlike an insulated wire antenna, the antennas were fed from a transmitter floating close to the sea surface. The attenuation through seawater in wireless or guided medium (insulated wires) depends on the conductivity and permittivity of seawater [Klein et al., 1977]. The experiments in this work were conducted exploiting surface wave propagation which reduces the influence of permittivity models.

In Chapter 2, we referred to buoy monitoring systems with elevated RF module raised from sea surface to a height of 2 m. This work emphasized the design of low height RF modules integrated with a hemispherical antenna for sea surface communications. The changes in efficiency, radiation pattern and propagation mechanism due to antenna-seawater interaction were reported and the advantages of hemispherical antennas for shallow seawater environment are outlined.

Hemispherical antennas due to their broad bandwidth offer high data rates and are advantageous for high speed wireless telemetry [Cardooso et al., 1993; Hui et al., 1999]. A theoretical and measurement analysis of hemispherical antennas has been reported in [Hui et al., 1999; Alsawaha et al., 2010]. The broad bandwidth of the hemispherical antenna further depends on the type of the radiating element. Replacing wire with a metal strip can further increase the bandwidth of such type of antenna [Alsawaha et al., 2010]. The broad bandwidth of this type of antennas is of benefit in floating buoys as the orientation of the antenna floating above the seawater surface is always changing, resulting in a shifting resonant frequency. If the antenna has a broad bandwidth, it will not be significantly out of resonance when the vertical position changes relative to the
Low-Profile Floating Hemispherical Antenna

water surface. This improves the link reliability and the data communications quality of service.

The radiation pattern of a hemispherical antenna is directed vertically as compared to a monopole which has a horizontal radiation pattern along the seawater surface. Vertical radiation pattern is helpful for information sensing from an elevated platform i.e. UAV or satellites. The antenna presented in this work is part of a large project, which involves the deployment of coastal water monitoring sensor networks in canal estates [Lemckert et al. 2006; Cosser` et al., 1989].

At 433 MHz, a hemispherical helical antenna requires a large ground plane to effectively direct radiation in the vertical direction. In this application, seawater (due to its high conductivity) is used as an infinite ground plane. Since seawater has an effect on the efficiency, a small sized copper ground plane was used to increase the gain of the antenna. We report a comparison of efficiency, bandwidth, propagation range between the hemispherical and a monopole antenna. Both antennas were tested for return loss measurements in the laboratory and propagation range measurements in the ocean near the shore. The variation in received power was also analyzed to monitor the link reliability of the channel. The antennas were optimized using the software CST studio suite [2016] and compared with the measured results.

Radio wave attenuation between floating transceivers depend on antenna height from the sea surface. The performance of the communication link is adversely affected by placing antennas near to sea surface which changes the propagation mechanism due to increased reflection angles. We modelled the communication link between transceivers using empirical models to estimate the losses in the volatile seawater environment.

The remainder of the Chapter is organized as follows. Section 5.2 describes the design of the hemispherical antenna. Section 5.3 discusses the measurement setup for return loss
and propagation range measurements. Theoretical and experimental results are presented in Section 5.4. Finally, Section 5.5 concludes and summarizes the work.

### 5.2 Antenna design Considerations

A hemispherical antenna is a modified form of spherical helix antennas. It was designed by winding a wire over a spherical surface. The spacing between the windings is constant. The helical structure of the antenna can be fully defined by the number of turns and the radius of the hemisphere. A hemispherical helix has advantage over spherical antenna for its compact size and stable structure. The resonant frequency of the hemispherical antenna is controlled by changing the radius of the sphere. The bandwidth of the antenna can be further increased by replacing the radiating element wire by a wider metal strip [Alsawaha, 2010].

The antenna was constructed on a floating Styrofoam buoy with a small copper ground plane inside the Styrofoam. The transmitter was sealed and enclosed in a cylindrical polyvinyl chloride (PVC) pipe (diameter 50 mm). A weight was attached to the bottom of the pipe for stability purposes and to reduce the fluctuations of the antenna in the water. A three and a half turn hemispherical antenna with a conducting ground plane is shown in. The antenna is made of a single conductor insulated wire. The geometrical parametric equations that represent the helical wire in spherical coordinates \((r, \theta, \phi)\) are [Hui et al., 1999; 2003]

\[
r = a, \quad \theta = \cos^{-1} \left( \pm \left( \frac{\phi}{2\pi N} - 1 \right) \right), \quad 2\pi N \leq \phi \leq 4\pi N
\]

(5.1)

where \(a\) represents the radius of the hemisphere and \(N\) is the number of equally spaced turns of the helix. The “+” and “−” signs represent the right and left hand helix, respectively. The hemisphere has a radius \(a = 9.3\) cm and a number of turns \(N = 3.5\).
The length of the helical wire ($L$) can be calculated by integrating the following equation [Hui et al., 2001]

$$L = \int_{0}^{\pi} a \sqrt{1 + (N\pi)^2 \sin^4 \theta} \, d\theta \quad (5.2)$$

The antenna simulation software CST, requires the antenna information in a cartesian coordinate system ($x, y, z$) for the corresponding spherical coordinates ($r, \theta, \phi$) which can be derived using the relationships ($x = r \sin \theta \cos \phi, y = r \sin \theta \sin \phi, z = r \cos \phi$) [Hui et al., 2001; Nitecki et al., 2012]. The radius of the hemisphere and number of turns define the length of the helical wire forming the hemispherical antenna. If the number of turns is constant, decreasing the radius of the hemisphere would decrease the length of the helical wire which would tune antenna to a higher resonant frequency. The design parameters ($a = 9.3\text{cm}$ and $N = 3.5$) resulted in $L = 105.1\text{cm}$.

The antenna was made from a single insulated copper wire and the diameter of the wire (conductor and insulation) is 2.2 mm, while the diameter of the conductor is 0.9 mm. A circular copper ground plane with radius 50 mm was used to fit a Styrofoam diameter that served as a float and support for the antenna shown in Figure 5—1. The coaxial feed has 50 $\Omega$ characteristic impedance. The antenna can be fed from the side or from the center of the sphere of the hemisphere. The center feed brings symmetry from the origin, however, it requires extra wire from the side to the center of the hemisphere. The side fed antenna requires no extra copper wire but has an effect on the symmetry characteristics.

The size of the ground plane influences the radiation characteristics of the antenna. Ideally, the radiation direction of a hemispherical antenna on an infinite ground plane is oriented in the z-direction.

A center fed hemispherical antenna with a center feed equal to the radius ($r = 9.3\text{cm}$) of the hemisphere is illustrated in Figure 5—1. The size of the ground plane is relatively small compared to the radius of the hemisphere. When the antenna is placed over
seawater, the conductivity ($\sigma > 4 \text{ S/m}$) of seawater has an effect on the radiation pattern of the antenna. This is discussed in further sections. Impedance matching was performed by introducing a small section of wire with length $h = 32 \text{ mm}$ (see Figure 5—1). When $h = 0$, the impedance of the antenna has a large capacitive reactance at the resonant frequency. By adjusting $h$, the antenna can be matched to 50 $\Omega$ at a desired frequency.

![Geometry of the 3.5 turn hemispherical helical antenna.](image)

5.3 Measurements

Two separate arrangements were used for return loss and seashore measurements. The return loss measurements were conducted in the laboratory while the propagation range measurements were performed in the coastal bay [Brown, 2013; Mogensen et al., 2014].

5.3.1 Setup for return loss measurements

Software CST microwave studio was used to adjust the antenna resonance at 433 MHz when floating in seawater. Since the water environment shifts the antenna resonant frequency due to the relative permittivity of the water ($\varepsilon_r = 80$), the antenna operates at a slightly higher frequency in air. The resonant frequency was controlled by changing the
radius of the sphere. TABLE 5—1 lists the CST simulation conditions for the designed antennas in free space and on the seawater surface. The spherical and monopole antennas were modelled at various submerged depths in water and the effect on the return loss was observed. The water environment was simulated using infinite (open) boundary conditions.

Table 5—1 CST Simulations of different hemispherical antennas

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Modeling</th>
<th>Boundary</th>
<th>Solver/Accuracy</th>
<th>Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 MHz to 1 GHz</td>
<td>3D curve</td>
<td>Open</td>
<td>Time domain/-50 dB</td>
<td>Waveguide</td>
</tr>
</tbody>
</table>

Figure 5—2 Setup for return loss measurements: The antenna was placed in a water-filled container with saline solution. The VNA was connected through a coaxial cable from the bottom of the container. A PVC pipe was used to enclose the ground plane. Figure 5—2 shows the water-filled container used for return loss measurements. A PVC pipe was inserted in the center of the container to keep the ground plane isolated from the water environment. A coaxial cable was connected between the bottom of the pipe through an SMA connector, to a portable Vector Network Analyzer (N9923A Field Fox Handheld RF VNA @6Hz). Balsa wood ($\varepsilon_r = 1.2$) was used to shape and support the helical antenna.
The white PVC coating on the wire insulated the copper to protect it from direct contact with the water. The water was doped with NaCl to a conductivity of 4 S/m. The temperature was measured using a Fluke 62 mini infrared thermometer, and the conductivity was measured using a WP-81 conductivity meter from TPS Pty Ltd. The return loss measurements for a quarter wavelength monopole antenna (17 cm) were obtained following the same procedure as the one used for the hemispherical antenna.

5.3.2 Setup for seashore measurements

Propagation range measurements were performed by connecting the antenna to a sensor node (see Figure 5—3) operating at 433 MHz, with programmable transmit power (-10 dBm, 0 dBm, 10 dBm). The transceiver has dimensions 60 mm × 40 mm, is battery powered and can operate in continuous wave (CW) or as Master/slave modes. In the Master/slave mode it can record the RSSI and packet loss information. More details about the transceiver can be found in [Aubry et al., 2015; Loni et al., 2017].

Figure 5—3 Floating hemispherical helical antenna setup. Thin Balsa wood was used to support the antenna. The Styrofoam sphere was used as a float with a ground plane attached to the orthodrome plane of the sphere. The PVC pipe contained the sensor and the adjustable weights used for stabilization in the water.
Figure 5—3 shows the floating buoy configuration for propagation experiments. The antenna was fixed on a Styrofoam sphere, with the ground plane attached to the orthodrome plane of the sphere with radius 9.3 cm. A PVC pipe 50 cm long and 4.5 cm in diameter was glued to the sphere through a hole at one of its sides. The sensor node was enclosed in the PVC pipe, as well as the weights required for stabilization. RSSI measurements were recorded using a portable RF spectrum analyzer from an RF explorer. The maximum possible power level observed at the RF explorer was -21 dBm and the minimum detected level was -116 dBm. The same configuration was used for the measurements with a monopole antenna. The Styrofoam sphere was modified, and a hole was made in the center of the sphere to fit into the PVC pipe containing the monopole antenna.

5.4 Theoretical and measurement results

5.4.1 Return loss measurements

Return loss measurements were performed to assess the effect of the saline water on the antenna characteristics. The effect of the water parameters, i.e. conductivity and permittivity, on the antenna characteristics was observed by submerging the antenna in a water container. Figure 5—4 shows the return loss measurements of the antenna at 433 MHz. The water conductivity was raised step-wise from 1 S/m to 4 S/m. The shift in the resonant frequency and changes in return loss were recorded for each conductivity level. Results showed that the resonant frequency shift was 116 MHz in water with a conductivity of 1 S/m. However, when the conductivity was raised to 4 S/m, the return loss changed significantly but with a very minor shift in resonant frequency. According to the Klein-Swift model [Klein et al., 1977], the relative permittivity of seawater ranges
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between 70 to 80 and it depends on the conductivity, temperature and salinity of water.

Figure 5—4 Measured S11 parameter for the hemispherical antenna in air and on seawater surface with the water conductivity increased from 1 to 4 S/m.

From this result, we can conclude that increasing the conductivity has an effect on the return loss and a very small effect on the resonance. The shift in resonant frequency depends on the operating frequency band and it becomes less significant at higher frequencies as reported in [James et al., 2010].

Figure 5—5 shows the simulated and measured results for the hemispherical helical antenna. In air, both the simulated and measured antenna designs resonated at 513 MHz and 506 MHz, respectively. Simulations for the antenna just above seawater surface and in partially submerged condition were performed using the infinite boundary conditions in the CST studio suite. The water-filled container discussed in the previous section was gradually filled with saline water and the change in return loss was observed. The return loss measurements occurred when the lowest loop of the antenna was completely submerged in water.

TABLE 5—2 shows a comparison of simulated and measured results for the antenna. The simulated results show that the antenna in water has a resonant frequency of 418 MHz, while the measured results show that the resonant frequency is 391 MHz.
bandwidth of the antenna in saline water increases significantly (simulated and measured values were 47% and 36%, respectively).

![Graph showing comparison of S11 parameter for the hemispherical helical antenna in air and saline water](image)

Figure 5—5 Comparison of simulated and measured S11 parameter for the hemispherical helical antenna in air and saline water surface with a conductivity of 4 S/m.

The bandwidth in saline water is approximately twelve times higher than air (see TABLE 5—2). The radiation efficiency drops to 57 % when the lowest loop (largest radius) of the antenna is submerged in seawater (see TABLE 5—2). This means that even in the worst-case scenario, when the antenna is partially submerged in seawater, the radiation efficiency is good for communication between sensor nodes.

<table>
<thead>
<tr>
<th>TABLE 5—2 COMPARISON OF ANTENNA DESIGN PARAMETERS (MEASURED AND SIMULATED)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HEMISPHERICAL ANTENNA</strong></td>
</tr>
<tr>
<td>Resonant Frequency $f_r$ (MHz)</td>
</tr>
<tr>
<td>Bandwidth (%)</td>
</tr>
<tr>
<td>Efficiency (%)</td>
</tr>
<tr>
<td>Air</td>
</tr>
<tr>
<td>Simulated</td>
</tr>
<tr>
<td>Measured</td>
</tr>
</tbody>
</table>

Figure 5—6 shows the return loss measurements for the monopole antenna using both simulation and measurements. TABLE 5—3 summarizes the results regarding bandwidth
and efficiency. The monopole antenna has almost the same shift in resonant frequency as the hemispherical antenna however; the efficiency of the monopole is significantly lower. From these results, we can conclude that the hemispherical antenna in seawater environment is comparatively more efficient. The efficiency for both the antennas could not be measured in the ocean.

---

**Figure 5—6** Comparison of simulated and measured S11 parameter for the monopole antenna in air and on sea water surface with a conductivity of 4 S/m.

**Table 5—3** Comparison of Antenna parameters for the Monopole antenna (Measured and Simulated)

<table>
<thead>
<tr>
<th></th>
<th>Resonant Frequency $f_r$ (MHz)</th>
<th>Bandwidth (%)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>air</td>
<td>water</td>
<td>air</td>
</tr>
<tr>
<td>Simulated</td>
<td>550</td>
<td>448</td>
<td>9.63</td>
</tr>
<tr>
<td>Measured</td>
<td>541</td>
<td>446</td>
<td>9.79</td>
</tr>
</tbody>
</table>

---

Figure 5—7a shows the horizontally-directed radiation pattern of the monopole antenna. The radiation pattern of the hemispherical antenna (see Figures 5—7b and 7c) over air and water surface is given in the x-z plane ($\phi = 0^\circ$) and in the y-z plane ($\phi = 90^\circ$). Figure 5—7b shows that the radiation of the hemispherical antenna over a copper ground plane is directed towards the positive z-direction ($\theta = 0^\circ$) with a large back lobe. The small size of the ground plane results in radiation towards the negative z-direction.
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(\(\theta = 180^\circ\)). Ideally, the hemispherical antenna on an infinite copper ground plane would not have a back lobe and almost all radiation would be directed in the positive \(z\)-direction. Figure 5—7c shows the radiation pattern when antenna is placed over the water surface and simulated for infinite boundary conditions.

The radiation pattern of Figure 5—7c is when the lowest loop of the antenna is submerged in seawater. Here, the water surface acts as an infinite ground plane and the back lobe of the radiation pattern disappears. The finite water conductivity results in a reduction of the
antenna efficiency.

### 5.4.2 Floating buoy measurements

Figure 5—8 shows the final design and set up of the floating hemispherical helical antenna with the beacon (transceiver) enclosed on the PVC pipe and a load attached. As discussed earlier, the antenna floating on the sea surface will experience a change in orientation which results in a shift in resonant frequency.

![Floating hemispherical helical antenna](image)

Figure 5—8 Floating hemispherical helical antenna with sensors enclosed in a PVC cylindrical pipe. The small ground plane is inside a Styrofoam float and isolated from seawater. Weights were attached at the bottom of the PVC pipe for improved orientation stability.

Figure 5—9 shows the set up for the propagation range measurements, where $d_{\text{LOS}}$ and $d_{sr}$ correspond to the line-of-sight and surface reflected distance between the antenna and the receiver, respectively. Here $h_r$ is the height of the receiver above the seawater level, and $d$ is the horizontal distance between the antenna and the seashore. The temperature and conductivity of the water was measured as 19 °C and 5.3 S/m, respectively. The spectrum analyzer was located on a rock wall at an elevation $h_r = 1.5$ m above the sea level. The first measurement was recorded with the antenna floating at a separation distance ($d = 5$ m). The weight was adjusted so that the ground plane was below the sea
surface level. The measurements were undertaken at calm seawater conditions with an approximate wave height of 5 ±0.5 cm. This will have an effect on the propagation. For each measurement, the buoy floated for 5 seconds until the RSSI reading on the spectrum analyzer stabilized. The procedure was repeated for the monopole antenna.

![Diagram of propagation range measurements](image)

Figure 5—9 Set up for propagation range measurements. The height of the transmitter is equal to the radius of the hemisphere, and the spectrum analyzer is placed onshore on a rock wall at 1.5 m above seawater level.

Figure 5—10 shows the comparison between the propagation range for the hemispherical and monopole antennas. The received power and distance are represented by vertical and horizontal error bars. The separation distance was increased until the signal level dropped below -100 dBm. For the hemispherical antenna, the signal power dropped to -92 dBm at a separation distance \(d = 135\text{m}\) which is almost the total width of canal estate. For the monopole antenna the signal power dropped to -100 dBm at a separation distance of 85 m. The error bars in Figure 5—10 show the variations in measurements since the floating buoy continuously changed its position and the dB level fluctuated. For the hemispherical antenna, the dB variation is represented by vertical error bars of ±2.5 dB and the position variation error bars are ± 0.5 m. For the monopole antenna, the variation in dB level was larger (±3 dB). The systematic variation for both measurements is the result of multipath interference between the direct path \(d_{LOS}\) and the ground surface reflected path \(d_{SR}\).
Figure 5—10 Received power level (buoy to base station) represented by error bars. The hemispherical power levels are represented by vertical error bars of 2.5 dB and monopole by 3 dB. The experiment was conducted at Cleveland (Brisbane, Australia) coastal area.

Figure 5—11 shows the propagation modeling of the measured data. WSNs for ocean applications have a reduced reliability due to the volatile seawater environment. In these situations, empirical models are the only possible solution. The attenuation of an EM wave for a floating sensor can be modelled by curve fitting the measurement data using multiple break points (or threshold), as compared to one slope model [Kurt et al., 2016]. For this purpose, the two-slope power law model (an improved form of the free space propagation model) was applied to the measurements at the canal estate. The two slope model uses a threshold ($d_b$) for the separation distance between transmitter and receiver and depending upon the distance, the model uses a $d^2$ path loss for ($d < d_b$) and a $d^4$ path loss for ($d \geq d_b$). TABLE 5—4 lists the path loss for the measurements with the two antennas. The reference distance was $d = 40$ m. For distances less than 40 m, both antennas approximate the $d^2$ path loss. After 40 m, the hemispherical antenna shows a $d^4$ path loss however the monopole antenna path loss is $d^8$. The break point (threshold) is variable and it depends on three important factors: transmit power, antenna efficiency and sea state. Since transmitter power was the same for the monopole and the hemispherical
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antennas, the propagation range is influenced by the antenna efficiency and the sea state. The threshold point is empirically selected and it may shift depending on the wave height, wind and water directions, and sea roughness. The received power is not directly proportional to the distance due to the fluctuations of the buoy.

The statistics regarding link reliability and packet loss information about buoy to base station propagation have been reported in [Loni et al., 2017]. The link reliability defined by packet loss was less than 2 % at 30 m under similar wave conditions.

TABLE 5—4 Power Law Path loss calculations for the Hemispherical and the monopole antennas [Kurt et al., 2016]

<table>
<thead>
<tr>
<th></th>
<th>$d_b &lt; 40\text{m}$</th>
<th>$d_b \geq 40\text{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemispherical</td>
<td>$y = -1.9965x - 3.6342$</td>
<td>$y = -4.1741x - 0.3578$</td>
</tr>
<tr>
<td>Monopole</td>
<td>$y = -2.0395x - 3.6672$</td>
<td>$y = -8.3012x + 6.2478$</td>
</tr>
</tbody>
</table>

Figure 5—11 Path loss calculation for the hemispherical and monopole antennas using the two-slope model [Kurt et al., 2016]
5.5 Conclusion

A hemispherical helical antenna at 433 MHz for coastal monitoring applications has been developed. The return loss measurements and simulations showed that this antenna can perform efficiently even in a partially submerged condition. A propagation distance of 135 m was achieved for sea surface to offshore base station communication link using a +10 dBm transmitter. This is a sufficient range for water monitoring in the canal estates (maximum width of 140 m). A comparison with a monopole antenna under the same conditions in terms of efficiency, propagation range and dB level, was performed. Seawater is used as an infinite ground plane which has the advantage of reducing the size of the sensor node. As the radiation is principally vertical, the sensor data from a floating hemispherical antenna can be collected from an airborne vehicle (for example a UAV, plane or satellite), a water vehicle (e.g. an autonomous glider, a manned boat, etc..) and a GPS reference can be established for each sensor node while the transmitter and associated electronics are submerged. Further work includes the improvement and testing of 3D printed hemispherical antennas at both 433 MHz and 2.45 GHz to explore possibilities of establishing a sensor network, which could be smaller in size and more robust.
Publications:

Statement of contribution to co-authored published paper

The contents of Chapter 6 were published in a peer-reviewed Journal. The bibliographic details of the paper are:


My contribution to the paper included antenna modelling, preparing setup for laboratory and field experiments, analysing theoretical and experimental results and drafting the paper.

Signed: Zia M. Loni Date: 26th October 2018

Countersigned: Hugo G. Espinosa Date: 26/10/2018

Countersigned: David V. Thiel Date: 26th October 2018
Chapter 6

Mechanical Design of a Floating Buoy

Following the study reported in Chapter 5 of a hemispherical antenna, an integrated waterproof enclosure was developed. The size of the copper ground plane for the hemispherical antenna was reduced by the conductive seawater forming as part of the ground plane. The effect of seawater conductivity on gain, efficiency and resonant frequency of a hemispherical helical antenna are reported. The presence of seawater increases the gain from 6 dBi (in air) to 8 dBi but with a decreased efficiency. The simulated radiation efficiency of the antenna on water surface is 61%. This work reports the design of a low-cost floating buoy. The buoy provides a waterproof enclosure for the circuitry and antenna. The buoy can be effectively used for shallow water coastal monitoring. This was reported in Radioengineering [Loni et al., 2018d].

6.1 Introduction

In this Chapter, we discuss the design and construction of a real-world floating buoy integrated with hemispherical antenna. A floating buoy must be waterproof to protect circuit electronics and antenna from severe environment hazards including rain and tides. Figure 6—1 shows the design of a floating buoy holding both the antenna and the circuit board electronics. Vacuum forming, and 3D printing technologies were used for the construction of the buoy. The advantages of these technologies have already been discussed in Chapter 2. These technologies promise low cost manufacturing and design freedom. Vacuum forming is used to build structures using a thermoplastic sheet. In this case, the sheet thickness was 2 mm and the material was Polyethylene Terephthalate
Glycol (PETG). The designed sensor buoy (Figure 6—1) is air filled. A circular copper ground plane lies horizontally on the axis of the sphere where the upper hemisphere is the antenna and the lower hemisphere contains the electronics and sensing equipment. The complete system is waterproof and can be used for monitoring water quality in shallow water coastal areas. The principal direction of the radiation pattern of the hemispherical antenna is directed in the vertical direction which is advantageous for collecting data through satellite or Unmanned Air Vehicles (UAV’s).

Figure 6—1 A spherical floating sensor buoy contains a copper ground plane on the horizontal axis. The upper transparent hemisphere contains the three and half turn Hemispherical antenna on 3D printed ABS material. The lower hemisphere contains the sensor electronics.

In addition to the construction of the buoy, we also performed return loss measurements with the upper half of the buoy which holds the hemispherical antenna. The use of seawater as ground plane was further investigated and the change in efficiency, resonant frequency and radiation pattern was analysed. We show how seawater conductivity can
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be used to our advantage if sea surface forms part of a ground plane of a low profile hemispherical antenna.

The Chapter is organized as follows; Section 6.2 discusses hemispherical antenna design and construction of floating buoy. Section 6.3 describes the simulations and measurement results of antenna on water surface. Section 6.4 discusses the conclusion and future work.

6.2 Antenna and buoy design

Hemispherical antenna has already been discussed in Chapter 5. In this section, we refer to the parametric equations used for antenna design in CST software [Hui et al., 1999; 2003].

\[
\begin{align*}
    r &= a \\
    \theta &= \cos^{-1} \left( \frac{\phi}{N\pi} \right) \quad 0 \leq \phi \leq N\pi \\
    L &= \int_{0}^{\pi} a \sqrt{1 + (N\pi)^2 \sin^4 \theta} \, d\theta
\end{align*}
\]  

The diameter of the ground plane is 120mm. Eq. (6.3) gives the length of the helical wire forming the hemispherical antenna which is equal to 79.2cm. The radiating element of the antenna is a single conductor insulated copper wire. The antenna is fed from the center by extending a wire from the side to the center of the hemisphere. The length of the center feed is equal to the radius of the hemisphere.

Figure 6—2 shows a vacuum formed structure for holding the antenna. In vacuum forming, as the heated plastic takes the shape of the mould under test, a 3D printed hemisphere with antenna indentations was designed in SolidWorks [2017] using the same design parameters as that used in CST modeling. The mould was placed in the vacuum forming apparatus under differential pressure and elevated temperature. Due to the tracks
on the printed hemisphere, the same tracks appeared on the inner surface of the plastic hemisphere in the form of narrow indentations. The radiating element (copper wire, See Figure 6—1 and Figure 6—2) was glued into this indentation. This structure protects the antenna from seawater and weather conditions.

![Image](image.jpg)

Figure 6—2 Vacuumed formed hemisphere with small width canals on the inner surface.

The lower part of the hemisphere holding the low power transmitter and ground plane was 3D printed with ABS material. Figure 6—1 and Figure 6—3 show the lower hemisphere which contains the ground plane and a low power transmitter. To improve the stability and to maintain orientation of the floating sensor buoy, an anchor location was also printed to add suitable weights. The upper and lower hemispheres were combined using a gasket which was also 3D printed. Given the upper hemisphere is optically transparent, photovoltaic cells can be placed on the ground plane for additional power of the sensor.
6.3 Measurements

6.3.1 Laboratory measurements

Figure 6—4 shows the setup for return loss measurements carried over a water surface in the laboratory. The measurements were performed in a plastic container with saline water. Sodium chloride (NaCl) was added until a conductivity of 5S/m was achieved. The copper wire (antenna) was glued to the indentation on the inner surface of the upper hemisphere. The antenna coaxial feed was fixed to the bottom of the container and the cable was connected to a Portable Vector Network Analyzer (N9923A Field Fox Handheld RF VNA@6GHz) through a SMA connector.

Two experiments were performed using a slightly modified arrangement between them. In the first experiment, the saline solution was used as a ground plane. This was achieved using an earth wire with one end connected to the SMA connector and the other end was exposed to the saline water (see Figure 6—5). In the second experiment, the hemispherical antenna was placed on a small copper ground plane floating in the saline water. The coaxial cable and SMA connector were pulled through a sealed pipe to protect the feed point from direct contact with the saline solution. The copper ground plane was insulated from the water.
The measurements were performed over a frequency range of 0 to 1 GHz. The saline solution was gradually poured in the water tub and the change in the return loss was measured. The measurements were recorded until the saline solution reached the lowest turn of the hemisphere. The conductivity level was monitored with a WP-81 conductivity meter from TPS Pty Ltd.

Figure 6—4 Setup for return loss measurements. The coaxial feed cable is fed through the bottom of the plastic container. The water conductivity was 5S/m.

Figure 6—5 Saline solution used as ground plane. One end of the earth wire was attached to SMA connector and the other end was exposed to saline water.

6.3.2 Results

Figure 6—6 shows the simulated and measured results when saline water was used as a ground plane for the antenna. Simulations showed a return loss of -30 dB at 465
MHz. The measured resonant frequency was recorded as 429MHz with a return loss of -38 dB. The simulated radiation efficiency for the antenna on the water surface was calculated as 19.5%. These results show that water as ground plane results in a significant reduction of radiation efficiency. This is too low for most practical applications. To increase the antenna efficiency, the copper ground plane with diameter 120 mm was included under the hemispherical antenna. The antenna with copper ground plane was first tested in air and then floating on the water surface.

Figure 6—6 Simulated and measured return loss measurements with seawater as ground plane.

Figure 6—7 shows the comparison of simulated and measured results for the antenna with copper ground plane. The simulated and measured resonant frequencies in air were recorded as 772 MHz and 765 MHz, respectively. On the water surface, the simulated and measured resonances were 723 MHz and 740 MHz, respectively. The frequency shift in the measured frequencies was 25 MHz, however; for simulated results it was calculated as 50 MHz. We can also observe that the water surface increased the bandwidth of the antenna. The simulated radiation efficiency of the antenna over the water surface was calculated as 61%. A comparison between the two experimental results (Figure 6—6 and Figure 6—7) shows that the antenna on the water surface is matched to a lower frequency,
i.e. 429 MHz. The introduction of the copper ground plane shifted the resonance to a higher frequency. The shift in resonance is due to the different surface impedance given by the seawater and the copper ground plane. The complex permittivity ($\varepsilon_r$) of the saline solution is a function of the operating frequency [Klein et al., 1977]. The permittivity values at 429 MHz and 740 MHz were calculated as 71-206i and 71-121i respectively [Klein et al., 1977; Loni et al., 2017].

Figure 6—7 Simulated and measured reflection coefficient (S11) for the hemispherical antenna in air and with the ground plane (120mm)

Figure 6—8 shows the simulated radiation pattern for the antenna arrangements discussed above. Ideally, a hemispherical antenna on an infinite ground plane would radiate in the vertical direction ($\theta = 0^0$) with no back lobe ($\theta = 180^0$). Simulation results for the antenna with copper ground plane in air shows a large back lobe. The reason is the finite size of the copper ground plane. The same antenna when placed on the water surface results in reduction of the back lobe with more radiation directed in the vertical direction [Loni et al., 2018a]. The saline solution behaves as a lossy ground plane, although there is no physical contact between the saline solution and the copper ground plane. The lowest gain was calculated when the saline solution was used as the ground plane. The reason for the low gain is the high radiation absorption by seawater.
Mechanical Design of a Floating Buoy

which reduces the radiation efficiency to less than 20%. These results show that the saline solution alone cannot be used as a ground plane. However, a combination of the copper ground plane and the seawater increases the gain at the cost of decreasing efficiency compared with an infinitely large conducting sheet. The size of the copper ground can be increased to improve the radiation efficiency. The copper ground (120 mm) increased the efficiency to 61% making it more suitable for installation in a sensor node. The size of the ground plane and radiation efficiency can be traded off depending on the application of the sensor node. Increasing the size would increase the efficiency of the antenna but the size of sensor node would increase too. This is not desirable for our ocean monitoring applications.

Figure 6—8 Simulated radiation pattern of the sensor buoy in air and over the saline water surface.

This antenna can achieve a significant propagation range with a low power transmitter. Figure 6—9 shows the prototype design for the floating buoy mounted with the hemispherical antenna. A low powered transmitter and copper ground plane are located within the sensor buoy. The design is waterproof, however; it can easily be opened to replace batteries and other electronic equipment. The buoy can be anchored by adjusting the weights located at the bottom of the structure. The radiation pattern of the hemispherical antenna (see Figure 6—8) is directed in a vertical direction with an 8 dB
Mechanical Design of a Floating Buoy

decrease in the back-lobe radiation and 2 dB increase in the vertical direction. This is advantageous for data collection from the floating sensor nodes. Real time information from the sensors can be retrieved by an Unmanned Air vehicle (UAV) flying over the sensor nodes or through remote sensing utilizing communication satellites.

![Prototype of vacuum formed hemisphere with antenna glued to the small width canals on the inner surface.](image)

Figure 6—9 Prototype of vacuum formed hemisphere with antenna glued to the small width canals on the inner surface.

6.4 Conclusion

Vacuum forming and 3D printing techniques were used to manufacture a low cost floating buoy prototype. The vacuum formed hemisphere protects the hemispherical helical antenna from environmental hazards which includes rain, high tides and ocean waves. The buoy includes a hemispherical antenna with a small ground plane. Seawater was partially used as a ground plane which increased the gain of antenna. The highly conductive seawater has resulted in transforming the radiation pattern which gives us the liberty to use a small sized ground plane. The simulated radiation efficiency was 61%. The designed buoy is low cost and can easily be modified to accommodate sensors for collecting information from oceanic environment. The propagation range measurements
can be performed with a low power transmitter (10dBm) which will influence the density (nodes per m$^2$) of the sensor network. The radiation pattern of the antenna is mainly directed vertically which is advantageous for communications with satellites or a passing UAV’s.
Chapter 7
Conclusion and Future Work

This thesis aimed to investigate the use of conductive ocean water in various radio communications systems. To overcome the effects of tides and multipath interference the antennas were positioned on the water surface and tethered with a flexible cable or designed as floating units. The option of using a cable to transmit Ultra high frequency (UHF) was explored in the hybrid communication system.

7.1 Achievements

The most significant outcome of this work is the calculation and measurement of a UHF attenuation in three different communication scenarios. A communication system operating at 433 MHz utilizing an input power of +10 dBm with a receiver sensitivity of -116 dBm was established. We have shown that higher MHz frequency with low transmit power can be used for ocean monitoring where the water depth is around 3 to 5 m. Using an insulated wire monopole antenna, we can transmit information from a submerged transceiver located at a depth of 1.5 m to sea surface which can further be transmitted across the ocean surface up to 40 m. Horizontal distances of more than 100 m were achieved when the submerged insulated wire was replaced with a coaxial cable. The solution is low cost, smaller in size with less complexity with reliable data transfer between transceivers under light wind conditions. A radio link between floating transmitter and onshore receiver reports a packet loss of only 1.7% at 30 m.

Two low profile antennas were assessed, the monopole antenna for sea-land communication and a hemispherical antenna for better communication with drones and
Conclusion and Future Work

Antenna-seawater interaction causes a resonant shift which at 433 MHz is between 80 to 120 MHz. The antennas were designed at higher frequency considering the frequency shift which is approximately 25% at 433 MHz. Hemispherical antenna on seawater showed a bandwidth of approximately 50%, and efficiency equal to 59% when the lowest loop of the antenna was submerged underwater. This is useful for link reliability in the volatile seawater environment since larger bandwidth keeps the radio source in resonance and higher efficiency ensures longer propagation range. A propagation range of more than 140 m was measured which is enough in terms of node density in Canal estate where the maximum width is approximately 200 m.

We established how seawater acting as ground plane of infinite extent was used to advantage in UHF radio communications. With the surface monopole antenna, seawater acted as an outer conductor for the insulated wire making it a lossy coaxial cable which resulted in an attenuation of 38 dB/m. In the hemispherical antenna design, seawater was used as an infinite ground plane which reduced the efficiency (59%) but shaped the radiation pattern in the vertical direction.

In addition to experimental work, we also modeled the propagation path between transceivers. Radio wave propagation through insulated wires was modeled using King et al. [1981] formulation for antenna submerged in seawater. Moreover, radio wave attenuation in seawater significantly depends on the operating frequency which was modeled using Debye formulation and Klein-Swift (KS) permittivity model. The results in Chapter 3 and 4 showed that our theoretical modeling (38 dB/m) for insulated wire submerged in seawater matches closely with the measured results.

Another most important outcome of this thesis is the mathematical modeling of wireless communications between floating transceivers. Low profile antennas affect the
Conclusion and Future Work

propagation mechanism and losses in the communication link cannot be accurately estimated with inverse square law. In Chapter 5, we reported a two-slope model to estimate the propagation loss between low height antennas.

The final successful outcome was the design and fabrication of a floating buoy. For this purpose, vacuum forming and 3D printing techniques were used to design a waterproof buoy which due to its transparent structure can use solar energy to fulfil its power requirements. The structure is well suited if the buoy is placed on or above sea surface. An antenna inside the vacuum formed structure is protected from the harsh environment. In addition, the size of the buoy is quite small (diameter < 20 cm), which is advantageous in unobtrusive deployment of more than one buoy in shallow seawater environment.

7.2 Limitations

- The use of a simple insulated wire for RF transfer from the seabed to the sea surface has limitations due to higher attenuation of seawater (38 dB/m). If the water depth is above 2 meters, then the insulated wire must be replaced with low loss coaxial cable so that higher power is delivered to the antenna resulting in a larger propagation distance across the sea surface.

- Theoretical modelling of the wireless channel in seawater environment has limitations due to the significant near field loss. Low profile antennas result in antenna-seawater interaction which lowers the efficiency and changes the propagation mechanism. Although, we successfully modelled the losses in insulated wires, the channel was modelled using empirical modelling (Two-slope model).
Conclusion and Future Work

- The hybrid architecture used in this work for bringing information from seabed has limitations for deep seawater monitoring. Data transmission from an ocean depth of more than 10 m would increase the length of coaxial cable which may be slightly impractical as the location of the floating antenna can move further away from the desired position vertically above the tether.

7.3 Future Work

- In deep seawater monitoring, we would suggest a hybrid acousto-optic system [Johnson et al., 2014]. They used optical signals for uplink transmission of high data rate and acoustic communication for low data rate down-link. This architecture is considered useful for long distance communications with AUV’s.
- Future work includes designing a UAV installed with the same hemispherical antenna operating at the same frequency. This UAV shall be used to collect data from floating sensors nodes. Sensors which can measure pH, water flow, salinity and temperature will be integrated with the transmission systems to monitor the water quality in a shallow water coastal region.
- Future work also requires experiments regarding maximum achievable data rates in the proposed communication system. Since we are using a transmission line through the seawater and the link reliability across the sea surface is adequate, the proposed system is believed to achieve high data rate communication.
- Most of this work was conducted at 433 MHz with a transmit power of 10 dBm. This work can be extended to other available ISM bands i.e. 2.45 GHz supplied with variable transmit power which also depends on the size and requirements of the underwater environment being monitored. Since the attenuation in seawater is
Conclusion and Future Work

frequency dependant, the downside of using 2.45 GHz would be reduced propagation distances.
References


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