CHAPTER-3

UNDERWATER WIRELESS SENSOR NETWORKS

About 71 percent of the world's surface is covered by water and out of which oceans hold a share of approximately 97 percent. Exploration of oceans is not restricted to study of marine life or to observe the different biological change underwater. It can provide a great deal of information regarding climate change, natural disasters, and can provide significant data which can give us information regarding the history of our planet. An efficient and reliable communication system is therefore the need of the hour to unveil the unknown.

3.1 Underwater Wireless Communication modes

There are a few ways to communicate underwater due to external challenges posed by the its environment. They are discussed as below:

- **RF Communication:** Because of the conducting nature of sea water, radio wave does not propagate quite well underwater. Attenuation is higher for the high frequencies; therefore, most of the commercial radio equipment cannot be used underwater as they operate in MHz and GHz ranges. To avoid this if we use the a very low frequency radio wave, then a large sized antenna would be required as it consumes a lot of power. The attenuation of electromagnetic wave in water for 2.4 GHz band is 1695 dB/m in sea, and 189dB/m for fresh water body.

- **Acoustic Communication:** This is most mature technology in underwater communication. The speed of sound in water is 1.5×10^3 m/sec while in air it is just 340 m/sec. It is majorly used because of its far distance communication capability but along with this it also possesses limitations like large signal attenuation, low bandwidth. Moreover, the report of Natural Resources Defense Council, the rising ocean noise is a serious impact on life of dolphins, whales and other mammals causing hearing loss or sometimes even turn fatal.

- **Optical Communication:** Light travels at a speed of 2.25×10^8 m/sec in water, which is very high as compared to sound wave. Moreover, visible light communication does not harm the marine life in any way. Higher bandwidth, faster communication, power efficient and lesser interference with noises are the benefits of light wave communication. The attenuation of 450-540 nm wavelength is much smaller than the other wavelengths of light. But the major challenge faced by optical communication is that it can only work in a closer range.

- **Hybrid Optical Acoustic Communication:** The limitations of both the individual technologies can be overcome by combining the two. An optimal network can be devised to appropriately use required technology at the right point of time. Depending upon the SNR value of signal at the receiver ends determines that which technology will be used to transmit the data. High, medium and low SNR allows the optical communication while the below threshold SNR requires acoustic communication. Other than this, multi-hop technique is also employed to transfer the data from source to sink node. For this purpose, different layer protocols have also been devised.

3.2 Acoustic Channel Modelling

To improve any type of communication significantly, we first need to study the channel of communication along with transmitter and receiver. The received signal can be accurately obtained for the transmitter signal if we can accurately model the channel between the nodes. The channel modelling is dependent on the following signal characteristics as it travels from transmitter to receiver:

- Location of the two nodes.
- Reflection, Refraction and diffraction of signal due to any obstacles present in the path.
- Relative motion of the nodes.
- Signal attenuation as it travels along the medium.
- Noise present in the channel

3.2.1 Acoustic Signal Attenuation

The performance of a wireless communication system is majorly dependent on the attenuation of its signals under the conditions offered by the channel. Stefanov et al. 2011, gives the equation (3.1) to model the underwater channel for acoustic signals:

$$A(d,f) = A_0 d^k a(f)^d \tag{3.1}$$

where A(d, f) is the amount of attenuation at frequency f and over a distance d, while A_0 is the Normalizing constant and k (spreading factor) has a value of 1.5. The absorption coefficient is used to find the loss due to absorption in the total path loss in underwater wireless communication and can be obtained empirically by using Thorp's formula. It gives $a(f)$ in dB/km for f in kHz as given in equation (3.2).

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

Fig 3.1 shows the relationship between absorption coefficient and frequency which comes out to be approximately linear.

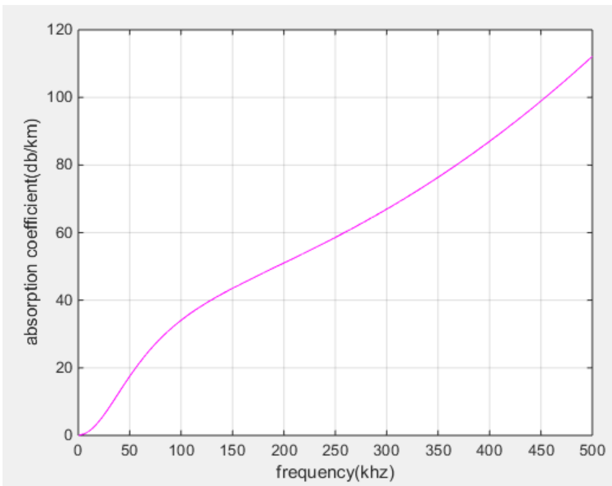

Fig 3.1 Absorption coefficient versus frequency

3.2.2 Environmental Noise for Acoustic Signal Communication

The ambient noise in the ocean can be modeled using four sources: turbulence, shipping, waves and thermal noise. Most of the ambient noise sources can be described by Gaussian statistics and a continuous power spectral density (PSD). The following empirical formulae give the power spectral densities of the four noise components in dB re μ Pa per Hz as a function of frequency in kHz. The noise from turbulences can be modelled from equation (3.3)

$$10\log\big(N_t(f)\big) = 17 - 30\log(f) \tag{3.3}$$

The noise from the shipping can be modelled from equation (3.4)

$$10\log\big(N_s(f)\big) = 40 + 20(s - 0.5) + 26\log(f) - 60\log(f + 0.03) \tag{3.4}$$

The noise from the waves can be modelled from equation (3.5)

$$10\log\big(N_w(f)\big) = 50 + 7.5\sqrt{w} + 20\log(f) - 40\log(f + 0.4) \tag{3.5}$$

The noise from the thermal noise can be modelled from equation (3.6)

$$10\log\big(N_{th}(f)\big) = -15 + 20\log(f) \tag{3.6}$$

where s is the shipping activity factor, $0 \leqslant s \leqslant 1$, and w is the wind speed in m/s. The overall PSD of the ambient noise is given in equation (3.7)

$$N(f) = N_t(f) + N_w(f) + N_s(f) + N_{th}(f) \tag{3.7}$$

3.3 Optical Channel Modelling

For Optical communication in underwater environment in a sensor node network, the channel must be modelled accordingly to act as one. The following sections give the pathloss model and the environmental noise effect which help in developing underwater scenario in the simulator.

3.3.1 Optical Signal Attenuation

One of the main targets in underwater optical wireless communication (UOWC) channel modeling is to evaluate the overall path loss for calculating signal-to-noise ratio. To calculate the optical path loss, Beer-Lambert's law, a simple exponential attenuation model, is applied.

$$I(z) = I_0\, e^{-c(\lambda)z} \tag{3.8}$$

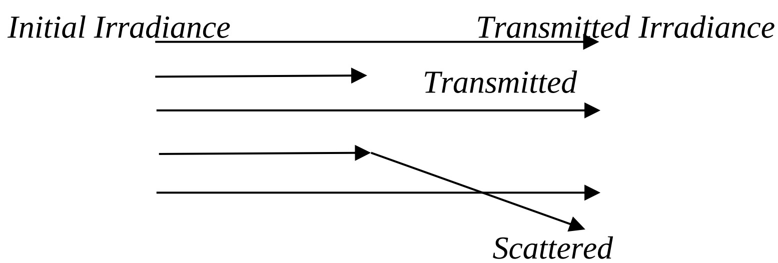

Fig 3.2. Illustration of Beer-Lambert's Law

Equation (3.8) gives the Beer-Lambert's Law which gives an expression for light received at a distance of z from the transmitter in a channel when the transmitted light is I_0 and attenuation coefficient is c(λ). The value of attenuation coefficients changes with different water types and water depths. In the underwater optics the relationship between the attenuation coefficient c(λ) and the scattering b(λ) and absorption coefficients a(λ) is given in equation (3.9).

$$c(\lambda) = b(\lambda) + a(\lambda) \tag{3.9}$$

The values of these coefficients with respect to the nature of the water are given in the Table 3.1.

Table 3.1 Typical values of a(λ), b(λ), and c(λ) for different water types

Water Type	**a(λ) (m^{-1})**	**b(λ) (m^{-1})**	**c(λ) (m^{-1})**
Pure Sea Water	0.053	0.003	0.056
Clear Ocean water	0.114	0.037	0.151
Coastal Ocean Water	0.179	0.219	0.298
Turbid Harbor Water	0.295	1.875	2.17

Beer-Lambert's Law implicitly assumes that the transmitter and receiver are perfectly aligned, and all the scattered photons are lost while in reality some of the scattered photons' arrival at the receiver is a probable event after undergoing multiple scattering.

3.3.2 Environmental Noise for Optical Signal Communication

To calculate SNR of the optical transmission we need to first calculate the Noise Equivalent Power (NEP) as given in equation (3.10). It is the total RMS value of the ambient light (such as solar) background shot noise, signal shot noise, the detector dark current shot noise and the preamplifier noise.

$$NEP_{total} = \sqrt{\left(P_{background_{shot_{noise}}}\right)^2 + \left(P_{signal_{shot_{noise}}}\right)^2 + (P_{dark\_current\_shot\_noise})^2 + (P_{preamplifier\_noise})^2} \tag{3.10}$$

Corresponding solar background shot noise is given by equation (3.11)

$$P_{solar} = \frac{\sqrt{2qS(BW_{en})P_{bg}}F}{S} \tag{3.11}$$

where q= electronic charge = 1.6×10^{-19} C

S = radiant sensitivity of the detector (A/W)

P_{bg} = Optical power of background

BW_{en} = Effective noise bandwidth= $\pi \cdot BW/2$

F = Excess noise factor =1 (for photodiode)

>1 (for APD)

Equation 3.12 gives the expression to calculate the optical power of the background (P_{bg})

$$P_{bg} = \frac{\pi^2 D^2 \cdot FOV^2 \cdot \Delta\lambda \cdot L_{solar}}{16} \tag{3.12}$$

where D = Diameter of the collecting optics

FOV = Field of view of the system in radians

$\Delta\lambda$= Wavelength bandpass

L_{solar} = Solar radiance calculated

Equation 3.13 gives the expression to calculate the solar irradiance.

$$L_{solar} = \frac{E \cdot R \cdot L_{fac} \cdot e^{-KD}}{\pi} \tag{3.13}$$

where E = Downwelling Irradiance

R = underwater reflectance of the downwelling irradiance

L_{fac} = factor describing directional dependence of underwater radiance

K = diffuse attenuation coefficient

D = Depth

K which is the diffuse attenuation coefficient (m^{-1}) is used to calculate the attenuation of diffuse light, such as sunlight, as it travels from the sea surface to various water depths. While calculating background noises, this parameter is required to calculate the attenuation of sunlight in ocean waters.

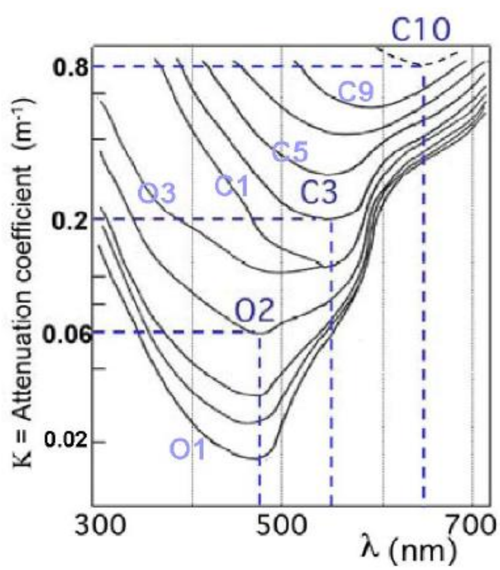

Fig.3.3 Variation of K with λ for Jerlov water types

Fig 3.3 shows Jerlov water types which range from the clear ocean values designated as O1, O1A, O1B, O2, and O3 where the higher numbers are for less clear water, and similarly for the coastal water types which range from C1 to C10.

Further, to calculate NEP_{total}, we need Signal Shot Noise which is given by equation (3.14)

$$P_{sig\_sn} = \frac{\sqrt{2qS(BW_{en})P_{sig}F}}{S} \tag{3.14}$$

where P_{sig} = Optical power of signal

For our calculations and our network simulation, we neglect the dark current shot noise and the preamplifier noises. Therefore, equivalent noise power is approximated as in equation (3.13).

$$NEP_{total} = \sqrt{(P_{background\_shot\_noise})^2 + (P_{signal\_shot\_noise})^2} \tag{3.13}$$

3.4 Channel Modulation

To establish wireless communicating links between nodes, the data needs to be modulated first and then transmitted for minimal losses. Most of the underwater optical systems are based on intensity modulation schemes, such as on-off keying and PPM (Pulse position modulation). Jingjing Wang et al. 2017, gives a model of how adaptive modulation technique can be used to communication over different ranges depicted in Table 3.2.

Table 3.2- Various types of modulation for underwater communication

Type of Modulation	**Advantages**	**Limitations**
OOK (On-off Keying)	Simple technique. Used for Low Speed optical communication.	Low energy and power efficiency
PPM (Pulse Position Modulation)	Higher energy Efficiency. Suitable for medium speed optical communication mode	Lower bandwidth utilization rate and complex trans receivers.

PSK (Phase Shift Keying)	1. Higher Energy Transfer Efficiency 2. strong anti-interference ability. 3. Used for transmitting over longer distances, therefore used with acoustic communication.	Acoustic signal has very low bandwidth, therefore cannot be used for sending multimedia.

Like the acoustic signals, the optical signals also experience attenuation in underwater environment due to scattering of light and significant absorption too. This degrades the Bit Error Rate of the system. Therefore, to reduce the impact of this attenuation, Forward Error Correction (FEC) channel coding techniques are employed. These techniques add redundant bits to the transmitted message to aid the receiver to correct the received message in case of errors. Though these codes improve the power efficiency of the system, but at the same time they decrease the bandwidth efficiency.

FECs have two categories:

- Block codes
- Convolution codes

Block codes are used in underwater optical systems due to their simplicity and robustness. The RS (Reed Solomon) code is generally used to avoid difficulty of system implementation and hardware resource consumption. Although the block codes are easy to implement but in the harsh environments like oceans and other turbulent waters with high interference, they do not give the desired performance. Therefore, we require more powerful and complex channel coding schemes like Turbo Codes. Turbo Code is like random code and is particularly suitable for long distance communication. It is not much affected by interference and attenuation, therefore is employed in rough environments. As during higher attenuation environment and for long distance communication, we don’t prefer optical communication in a hybrid medium, thus we use this code in an acoustic link. Table 3.3 shows the different channel codes for underwater communication.

Table 3.3- Various channel codes for underwater communication

Channel Codes	**Comments**
Reed Solomon	Simple, robust block code
BCH	Simple, robust block code
CRC	Simple Error Detecting code
LT	Practical Fountain code
LDPC	Complex linear block code.
Turbo	Complex convolution code.

3.5 Node localization

All neighbouring nodes need to know each other's location to form an efficient communication network. There are two types of nodes in any network- first the ones which need to be located, and the others which are the reference/anchor nodes. The latter ones assist in the localization process. Since the techniques of GPS does not work inside water due to inability of RF waves to travel inside water, therefore the node localization techniques are broadly classified into two categories.

1. Range Based Schemes: These schemes are based on bearing information to estimate their location relative to other nodes in the network. They rely on the following approaches to make measurements:

- Time of Arrival (ToA)
- Time Difference of Arrival (TDoA)
- Angle of Arrival (AoA)
- Received Signal Strength Indicator (RSSI)

V. Chandrasekhar et al. 2006 surveyed various methods adopted in UWSN and found out that while RSSI based schemes only provided a ranging accuracy of a few meters while with ToA based schemes an accuracy of a few centimeters could be achieved. With RSSI the problems of large variances in reading, multi-path fading, irregular signal propagation patterns and interference from background noises are to be tackled with. Therefore, it is advisable to use ToA/TDoA over RSSI for underwater scenario as the mode of communication is acoustics.

2. Range Free Schemes: These schemes do not use the approaches like ToA, TDoA, RSSI to estimate the distances to other nodes. They are broadly classified into:

- Hop count based schemes
- Area Based schemes

These schemes are fairly simple as compared to the formerly discussed ones. However, they provide only a coarse estimation of the location of a node. Due to this limitation, they are primarily employed in terrestrial WSN not in Underwater WSN.

3.6 Routing Protocol

The UWSNs consists of significant number of sensor nodes arranged at different depths throughout the region of interest. The nodes located at the sea/ocean bed cannot communicate with the surface buoys directly, thus multi-hop communication is needed which is then assisted by a routing algorithm. An efficient routing scheme should provide optimal route between the source and the sink. Designing a routing protocol depends on the requirements of the application of the network, as well as the desired level of precision and optimization, which furthermore depends on availability of the resources. G. Han et al. 2015, provide the comparison between various routing protocols used for Underwater WSN. They have classified the protocols into the following categories:

- **Energy-based routing**: It is an Energy Optimized Path Unaware Layered Routing Protocol (E-PULRP). The whole network is divided into layers with each node of a layer allowed to communicate to sink via equal number of hops. In the communication through multihopping, the choice of relay nodes is based on the latter’s distance from the sink node i.e node, more closer to the sink and significantly away from source becomes the next hop. The lifetime of network increases by allowing non active nodes to sleep. But in the is protocol the mobile nature of nodes is not considered, therefore making it unsuitable for real time underwater applications. Another energy based protocol is QELAR which has been discussed in T. Hu and Y. Fei, 2010, which is specifically suitable for mobile UWSNs. However, this demands the nodes to keep a lot of information in store due to the Q-Learning algorithm it uses, therefore, it is not possible to apply QELAR on a large scale UWSNs.

- **Geographic Information-Based Routing:** The position or location-based routing approach is also used in various protocols which continuously updating of the location of the neighbouring nodes is done to communicate data. Different protocols like Hop-by-Hop Dynamic Addressing Based (H2-DAB), Depth-Based Routing (DBR) and Delay Sensitive Depth-Based Routing (DSDBR) protocol have been discussed in M. Ayaz et al 2012.

3.7 Hybrid Opto-Acoustic Underwater Wireless Sensor Network

The performance of separate UOW systems can be severely degraded by the absorption and scattering effects of sea water, channel turbulence, misalignment errors and other impact factors. All these undesirable factors can cause frequent communication failure. Compared with UOWC, underwater acoustic communication method benefits from its mature technology, long link range and lower pointing requirements, but suffers from low data rate, low security and bulky instruments. On the other hand, UOWC systems can achieve high speed point-to-point data transmission, but they cannot operate in long distance and turbid environment. Considering the pros and cons of these two methods, hybrid link configurations are required to enhance the reliability of underwater communication system. The hybrid UWC system utilizes the advantages of each communication method.