Underwater communications

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SAŽETAK

Podvodna komunikacija je tehnologija za prijenos informacija u podvodnom okruženju. Ove tehnologije suočavaju se s raznim izazovima, kao što su prigušenje signala, raspršenje i refleksija signala zbog apsorpcije zvučnih ili elektromagnetskih valova u morskoj vodi. Kako bi se prevladali ovi izazovi, razvijeno je nekoliko tehnologija, uključujući podvodnu akustičku, optičku i elektromagnetsku komunikaciju, te akustičku komunikaciju. Akustička komunikacija pruža najveći domet, ali najnižu brzinu prijenosa, te je izložena slabljenju uzrokovanom slanošću, temperaturom i tlakom, na koje dodatno utječe dubina mora. Optička komunikacija pruža visoku brzinu prijenosa, ali je ograničena u smislu dometa zbog fluktuacija vode ili zahtijeva korištenje optičkih kabela. Elektromagnetska komunikacija je najmanje istražena tehnologija od ovih triju i nudi brojne prednosti u odnosu na druge vrste komunikacije, ali trenutna najveća prepreka je visoko prigušenje u podvodnim uvjetima. Podvodna komunikacija se najčešće koristi u civilnom sektoru, znanstvenim istraživanjima, vojnim operacijama i istraživanju nafte u moru.

Ključne riječi: Podvodne komunikacije, podvodne akustične komunikacije, podvodne optičke komunikacije, podvodne elektromagnetske komunikacije.

SUMMARY

Underwater communication is a technology for transmitting information in an underwater environment. These technologies face various challenges, such as signal attenuation, scattering, and reflection of signal due to seawater absorption of sound or electromagnetic waves. To overcome these challenges, several technologies have been developed including underwater acoustic, optical and electromagnetic communications, and acoustic communications. Acoustic communications offer the longest range but slowest transmission rate, it suffers to attenuations caused by salinity, temperature and pressure which are further influenced by depth of the sea. Optical communications offer high transmission rate but are limited in terms of range caused by fluctuations of the water or demand the use of optical cables. Electromagnetic communications is the least researched technology of these three, it offers numerous benefits compared to other communication types but current biggest obstacle is the high attenuation of underwater conditions. Underwater communications are most commonly used in civilian sector, scientific research, military operations and offshore oil exploration.

Keywords: Underwater communications, underwater acoustic communications, underwater optical communications, underwater electromagnetic communications.

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1. INTRODUCTION

Communication plays a vital role in the modern world, and its significance is clearly seen in various fields, including the marine environment. The ocean covers majority of the earth's surface (71%), and its deepest point is 11,022 meters. The immense expanse of water presents unique challenges for establishing effective communication, especially when it comes to transmitting data and information over long distances. As a result, development of underwater communication technologies has become crucial for various applications, such as scientific research, offshore oil exploration, and military operations. Underwater communication can be categorized into three main categories: acoustic, electromagnetic, and optical. Each of these categories has its advantages and disadvantages, depending on the specific requirements of its application. Acoustic communication uses sound waves to transmit data and information in seawater. Acoustics is ideal for long-range communication, as sound waves can travel over long distances without significant attenuation. However, acoustic communication is limited in terms of data transmission rates and bandwidth. Optical communication uses light waves to transmit data and information in seawater, they offer high data transmission rates and bandwidth and is ideal for short-range communication. However, the range of optical communication is limited, and it is susceptible to attenuation caused by the scattering and absorption of light waves in seawater. Electromagnetic communication involves the use of radio waves or other forms of electromagnetic radiation to transmit data and information in seawater. When compared to acoustic and optical communication, electromagnetic communication provides higher data transmission rates, greater bandwidth, and lower latency. Nonetheless, electromagnetic waves are significantly attenuated in seawater, which restricts the range of communication systems. Electromagnetic communication is currently the least explored option among these three methods. It has a potential of very high transmission rate enabling fast communication and piloting of underwater drones, major issue with electromagnetic communications is high attenuation and a very short range as a product of the before mentioned attenuation. This thesis will cover basic fundamentals of each communication type and serve as an introduction to them, later it will cover practical industrial applications.

2. UNDERWATER ACOUSTIC COMMUNICATIONS

Underwater acoustic communication is a method of transmitting information through sound waves in water. It is used in a wide range of fields, including oceanography, underwater exploration, underwater military operations, and offshore oil and gas exploration. The fundamental working principle of underwater acoustic communication is to convert electrical signals into sound waves that can be transmitted through the water. These sound waves can travel long distances, but their transmission is affected by various factors, which are water temperature, salinity, and depth. To overcome these challenges, specialized underwater acoustic communication systems have been developed, which use sophisticated signal processing techniques to optimize the transmission of signals. These systems use different types of modulation schemes, such as frequency-shift keying (FSK) and phase-shift keying (PSK) [1], to encode information into the sound waves. Other difficulties of underwater acoustic communications include limited bandwidth, high attenuation and multipath propagation.

2.1. THEORY OF UNDERWATER ACOUSTIC COMUNICATION

2.2.1. History of underwater acoustic communications

The ability to communicate underwater has been a crucial aspect of marine technology since the early 20th century, with the development of sonar technology for submarine detection during the first world war. Since then, advancement have been made in the field of underwater acoustics, including the development of hydrophones which were analogue modulated technology, they primarily used the SSB (Single Sideband modulation) and operated on 8-11kHz wavelenght, appearance of higher level of integrated circuits and transducers for receiving and transmitting acoustic signals, which have paved the way for modern communication systems. During the 1960s and 1970s, the United States Navy and other organizations began experimenting with long-range acoustic communication systems for use in submarine communication and underwater search. These early systems used low-frequency sound waves which enabled long distance communication underwater without significant attenuation, main issue was the limited transmission rates and the system was not immune to interference from other acoustic sources in the ocean. In 1980s commercial interested in underwater communications began to grow, mostly in the oil and gas industry for offshore exploration and drilling, this led to the appearance of acoustic modems which enabled transmission of data through acoustic signals. The first commercial acoustic modem was developed in 1985 by the French company Alcatel Submarine Networks. These early acoustic modems were capable of transmitting data at speeds of up to 300 bits per second. Followed by future improvement of acoustic modems in 1990s, efficiency in terms of data transmission rates and reliability, and the development of new signal processing techniques such as spread spectrum modulation, allowed for more efficient use of the bandwidth and reduced interference from other acoustic sources in the ocean. In recent years, advances in technology have allowed for the development of high-speed acoustic modems capable of transmitting data at rates of up to several kilobytes per second followed with wide range of applications in underwater surveillance, marine biology, and oceanographic research. Notable recent development is the use of unmanned underwater vehicles for underwater exploration and data collection equipped with high-speed acoustic modems and sensors allowing for communication between other underwater vehicles, and communication of vehicle to surface.

2.2.1. Velocity of underwater acoustic wave

Sound waves are vibrations that move through the air or water, which our ears can detect and interpret as sound. In water, sound waves are longitudinal waves, meaning that the particles in the water move back and forth in the same direction as the wave. The velocity of sound in water depends on the density of the water and its ability to compress and expand. Salinity, pressure, and temperature of the water affect its density and compressibility, which ultimately affects the velocity of sound in water. Generally, as pressure, temperature, and salinity increase, the velocity of sound in water increases as well. Temperature is the most significant factor affecting the velocity of sound in water. There are four layers in the sound velocity profile of underwater sound waves, the surface layer, seasonal layer, permanent thermocline, and deep isothermal layer. In the surface layer, which is several meters deep, the wind mixes the water and makes the temperature and salinity relatively the same. This layer is called the mixed layer, and the sound velocity remains constant. In the deep isothermal layer, the water temperature is always around 4 degrees Celsius [1], but the pressure changes. This pressure difference is the main reason for changes in the velocity of sound, creating a positive gradient of sound velocity [1]. In the seasonal thermocline layer, the increase in the water depth causes the temperature to drop rapidly, but compared the permanent thermocline layer the pressure and salinity increase with depth cannot compensate for the reduction of velocity caused by the temperature drop, creating a negative gradient in the graph. In the seasonal thermocline layer, negative gradient also changes depending on the season. However, in the permanent thermocline layer, the negative gradient stays relatively the same throughout the year. Velocity of sound is an important property for sonar equipment, which is used to detect objects underwater. To measure sound velocity, a sound velocity meter is used. It works by emitting high-frequency pulses in a known path and measuring the time it takes for the pulse to travel the distance. The sound velocity meter can then calculate the speed of sound in the water by diving the distance travelled by the time it took to travel that distance. This method is very accurate, with an accuracy of about 0.1%. When it comes down to the intensity of the sound waves underwater, they decrease gradually as they propagate over the distance.

2.2. STRUCTURE AND ANALYSIS OF UNDERWATER ACCOUSTIC COMMUNICATION SYSTEM

2.2.1. Structure of UWAC

Underwater acoustic communications are typically digital communication systems composed of several key components. These include receiving and transmitting transducers, decoder, an encoder, modulator, demodulator, and a channel used by underwater acoustic waves. Next is a brief overview of the basic functions of each component of the system.

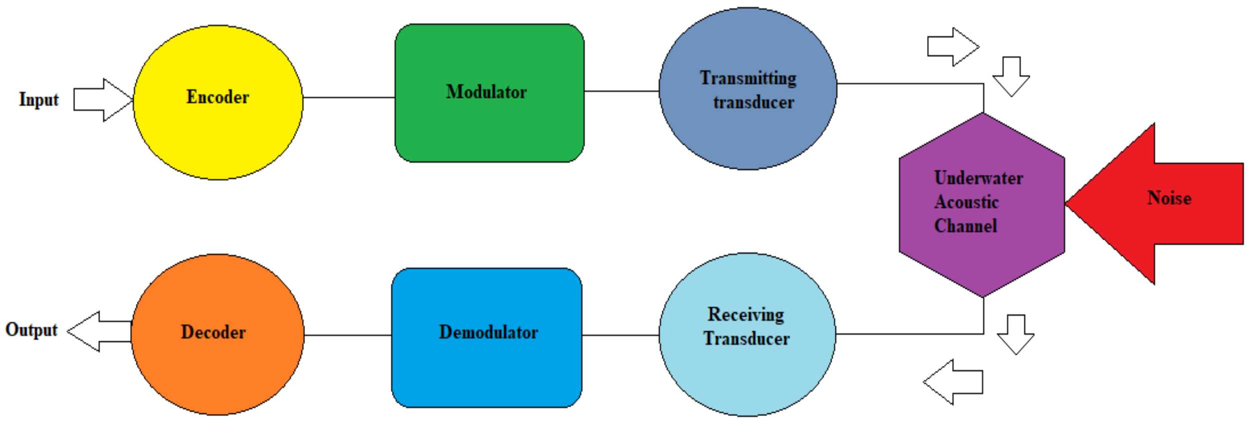


Figure 1 Block diagram of typical underwater acoustic structure

Source: Made by student in MS Paint

2.2.1.1. Encoder/Decoder

The digital communication system comprises the coder and decoder, which encompass the source encoder and decoder and the channel encoder and decoder [1]. The source signal output from the digital communication system may be in analog or digital form, which requires conversion into binary digital signals for transmission. This procedure is called source coding. The reverse procedure of converting binary digital signals into analog or digital source output is known as source decoding. The device that carries out these functions is called a source encoder or transcoder. In some digital communication systems, such as image transmission systems, source coding is also required to compress the data and facilitate dynamic image display within a limited time [1]. Due to imperfection of the communication system and the interference of noise, errors may arise during the conveyance of digital signals, which can result in reduced quality of the conveyed information. To minimize errors, error control techniques are used, such as error correction coding or decoding or error control coding or decoding [3]. These techniques belong to the category of channel coding and primarily focus on error detection, error correction, and basic implementation methods. To achieve error control, the encoder creates redundant or supervisory elements based on the input, while the decoder detects or corrects error using these coded elements. If other coding techniques are used to enhance the performance of the communication system, the corresponding encoder and decoder are also required. For instance, in multiple-input multiple-output systems for underwater acoustic communications, spatial diversity is often achieved by using space-time coding. Therefore, a space-time encoder and decoder is also incorporated into the system.

2.2.1.2. Modulator/Demodulator

After the encoder, a digital baseband signal is produced. If this signal is conveyed directly, it is known as a digital baseband transmission, which is limited in range to wired channels [3]. To convey wireless signals over longer distances, a carrier wave is required. The process of converting a digital based signal onto a carrier wave is called modulation, which transforms the digital signal into a particular frequency band suitable for conversion through a channel [1]. Common digital modulation techniques include amplitude-shift keying, phase shift-keying, and frequency-shift keying. With later two being popular in underwater acoustic communication systems, more on them later. Demodulation is the reverse process of separating the baseband signal from the modulated carrier signal and occurs on the receiving end.

2.2.1.3. Channel Noise

A channel refers to the signal path in any conversion medium, which can be thought of as a band of frequencies through which a signal is conveyed. However, the same band of frequencies can also restrict or degrade the signal [1]. The underwater acoustic channel is a wireless conversion channel that uses sound waves to carry information through water. The conversion characteristics of the water medium and the border or limit conditions, such as the surface and seafloor, are complex and variable, leading to significant impact on signal transmission [3]. Noise is a term used to describe the interference and noise that are inherent in various devices and channels in communication system.

2.2.1.4. Synchronization

In digital communication systems, synchronization is a crucial aspect that ensures that the transmitter and receiver are aligned in time and frequency. Synchronization encompasses carrier, bit, frame synchronization and other related processes [3]. It is essential for proper functioning and optimal performance of the communication system.

2.2.2. Performance of underwater acoustic communications

2.2.2.1. Transmission Rate

The symbol transmission rate, also known as the baud rate or code transmission rate, is the number of codes or symbols transmitted by a communication system per unit time and is measured in baud (B) [1]. It is related to transmission time T by the formula $RB = \frac{1}{T}$,

2.2.2.2. Information Rate

The information rate in acoustic signals refers to the amount of data that can be transmitted per unit time over an underwater communication channel. It is affected by several factors, including the available bandwidth, signal-to-noise ratio, and the modulation scheme used. In underwater communication, the available bandwidth is limited due to the high attenuation and dispersion of sound waves in water. Therefore, communication systems must be designed to use the available bandwidth efficiently. This can be achieved by using advanced modulation schemes, such as Quadrature Amplitude Modulation (QAM) and Phase-Shift Keying (PSK), that allow multiple bits to be transmitted per symbol. Additionally, coding schemes can be used to increase the data rate by reducing errors and improving the signal-to-noise ratio. The signal-to-noise ratio is a measure of the quality of the received signal relative to the background noise. It is affected by the distance between the transmitter and the receiver, the propagation path, and the presence of noise from sources such as marine life and ambient noise. To achieve high data rates, communication systems must be designed to operate at high signal-to-noise ratios. Information rate is also heavily impacted by modulation scheme, higher-order modulation schemes such as 64 or 256-QAM will offer higher data rates but are more susceptible to interference and noise.

2.2.2.3. Frequency band utilization

Frequency band utilization in underwater acoustic communications is critical to the effective and efficient transmission of information through the underwater channel. Again, due to the high attenuation and dispersion of sound waves in water, the frequency band available for underwater acoustic communications is limited. The frequency band utilized for underwater acoustic communications typically ranges from a few hundred Hz to a few tens of kHz. Frequency band is split into different sub-bands, each with its own purpose. These sub-bands allow us to use specific frequencies for different types of communication, like navigation, telemetry, and data transfer. Low-frequency bands are great for long-range communication because they can travel through water for a long distance (few kilometres). The only downside is that they don't have a lot of bandwidth, which means they can only transmit a limited amount of information at a time. On the other hand, high-frequency bands offer more bandwidth, allowing us to send larger amounts of data. But the catch is that these bands are more prone to signal loss and distortion due to their susceptibility to attenuation.

2.2.2.4. Error Probability

Error probability in short is a critical factor that determines the reliability of the communication system. The error probability can be influenced by various factors, including the lenght between the transmitter and the receiver, the modulation and coding schemes used, the signal-to-noise ratio, and the interference from other sources. To reduce the error probability in underwater acoustic communications, advanced modulation and coding schemes can be used. For instance, forward error correction coding can be employed to add redundancy to the transmitted data and enable the receiver to detect and correct errors. Additionally, error detection techniques such as cyclic redundancy checks can be used to identify and discard corrupted data.

2.2.3. Characteristics of underwater acoustic channels

2.2.3.1. Multipath Propagation

Multipath propagation is a phenomenon that occurs when sound waves travel through water and encounter different obstacles, such as reflections from the seafloor, surface, and other objects. This results in several copies of the original sound wave arriving at the receiver at different times and angles. In underwater acoustic communication, multipath propagation can cause signal distortion and loss, which can lead to communication errors and reduced system performance. To mitigate the effects of multipath propagation, there are various techniques, including signal processing, equalization, and beamforming. Signal processing involves the use of algorithms to extract the desired signal from the received waveform by filtering out unwanted noise and interference. Equalization is a technique used to adjust the frequency response of the communication system to compensate for the effects of multipath propagation. Lastly beamforming is a method that uses an array of hydrophones to steer the transmitted signal in a specific direction, reducing the impact of multipath propagation. Despite these techniques, multipath propagation remains a significant challenge in underwater acoustic communication. This is due to the complex and dynamic nature of the underwater environment, where the sound speed, temperature, and salinity can vary significantly over time and space. Additionally, the presence of marine life and other sources of noise can further complicate the problem. Particularly in shallow horizontal channels, multipath transmission occurs when the acoustic signal is reflected, refracted, and scattered repeatedly at varying times next to different path before it comes to receiver [1][8].

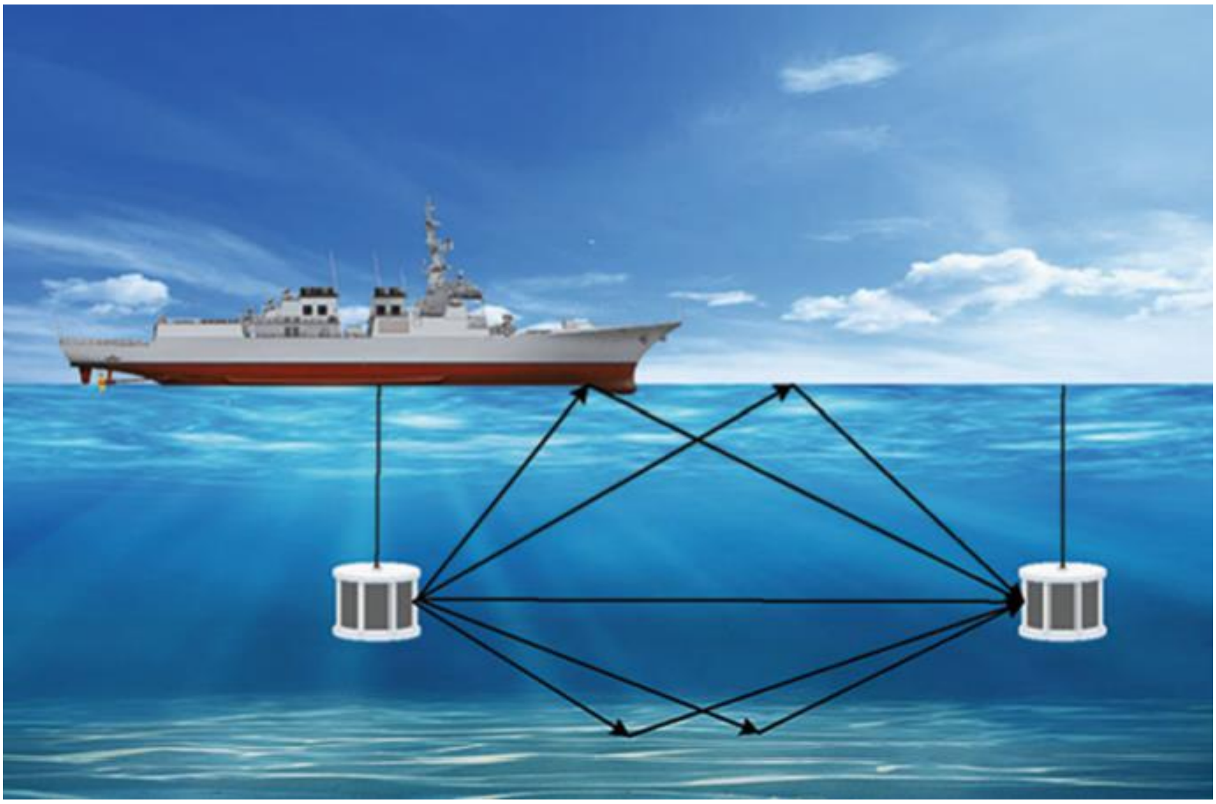


Figure 2 Schematic diagram of multipath signal propagation in UWAC

Source: Y. Lou, N. Ahmed,: *Underwater Communications and Networks (Textbooks in Telecommunication Engineering)*, 1st edition, Springer Cham, 2022,

This phenomenon produces phase shifting and fading of the transmitted signal, making the eliminations of disruptions from multipath transmission a primary challenge for underwater acoustic communications. In contrast to electromagnetic communications, communication signals are not reflected multiple times, the propagation velocity of underwater acoustic signals is about 1500 m/s [9].

2.2.3.2. Other effects on underwater acoustic channels

Most common other effects on underwater acoustic channels are doppler effect, expansion loss, and acoustic absorption. The Doppler effect is a phenomenon that occurs when there is relative motion between a sound source and a listener. In the context of UWAC, this effect can occur when either the source of the sound or the listener is moving relative to the water in this case the transmitter and receiver. If the transmitter is moving towards the receiver, the frequency of the sound waves will appear to be higher than their actual frequency, resulting in a "higher pitched" sound. Conversely, if the sound source is moving away from the listener, the frequency of the sound waves will appear to be lower than their actual frequency, resulting in a "lower pitched" sound. This is known as the Doppler shift. Expansion loss is a type of transmission loss that occurs as sound waves propagate through water and the distance from the sound source increases. As the sound waves travel through the water, they begin to spread out in all directions, resulting in a decrease in the intensity of the sound. This effect is known as spherical spreading and is a natural consequence of the way sound waves propagate in three dimensions. In general, the amount of expansion loss increases with the square of the distance from the sound source. In UWAC it can have a significant impact on the range and clarity of acoustic signal. For example, in sonar systems used for submarine detection or underwater mapping, expansion loss must be accounted for when calculating the range of the system and the strength of the returned signals. Acoustic absorption a process by which sound energy is absorbed and converted into heat as sound waves propagate through a medium. In underwater acoustics, the absorption of sound waves occurs due to the interaction of the sound waves with the water molecules. Water molecules are capable of absorbing sound energy at specific frequencies, depending on the temperature, pressure, and salinity of the water. In general, higher frequencies are more easily absorbed by water molecules, while lower frequencies can travel further before being absorbed [1][8].

2.3. MODULATION OF UNDERWATER ACOUSTIC WAVES

Modulation is the process of varying one or more parameters of a carrier wave to convey information. In underwater acoustics, modulation is used to transmit information by varying the amplitude, frequency, or phase of an acoustic carrier wave. There are several types of modulation techniques used in underwater acoustics, including amplitude shift keying (ASK) modulation, frequency shift keying (FSK) modulation, and phase shift keying (PSK) modulation [1]. In ASK, the amplitude of the carrier wave is varied to represent the information, while in FSK the frequency of the carrier wave is varied. In PSK, the phase of the carrier wave is varied to encode the information. In addition to analog modulation techniques, there are digital modulation techniques such as binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), are also used in underwater acoustics. Digital modulation techniques provide higher data rates and better noise immunity compared to analog modulation techniques and are commonly used in modern underwater communication and sensing systems [1].

2.3.1. ASK Modulation

. Amplitude shift keying (ASK) modulation is a digital modulation technique that uses the amplitude of the carrier wave to represent binary data. In ASK modulation of underwater acoustic signals, the amplitude of the carrier wave is varied to represent the digital signal being transmitted. This can be achieved by turning the carrier wave on and off or by varying its amplitude between two predetermined levels. One of the advantages of ASK modulation is its simplicity, as it only requires a simple modulation circuit at the transmitter and a demodulation circuit at the receiver. However, ASK is more susceptible to noise and interference than other digital modulation techniques, such as frequency shift keying, or phase shift keying. In UWAC systems, to circumcise the effect on amplitude oscillation of the acoustic signal most often ASK in UWAC uses the on-off keying, most straightforward method for amplitude keying. In this keying method, the carrier wave signal is turned on or off to represent binary 1 or 0, respectively. For demodulation two methods are possible, either coherent (i.e., envelope detection method) or non-coherent demodulation. Non-coherent method reconstructs the original signal without the need for additional processing. While coherent method reconstructs a synchronized carrier wave at the receiver [1].

2.3.2. Frequency Shift Keying Modulation

Frequency Shift Keying (FSK) Modulation is a non-coherent modulation that is suitable for the time and frequency expansion of UWAC channel [1]. Benefits of FSK modulation include ability to transmit acoustic signals over long distances, 4000m in horizontal shallow waters and vertically 3000m with a low amount of false bit rate and high reliability of the system. However, the main issues with this modulation include low band utilization, wide bandwidth, and a high signal-to-noise ratio requirement. When it comes down to demodulation, FSK as in AKS is possible to be categorized into non-coherent and coherent demodulation. In real world applications the non-coherent demodulation is primarily used. This method consists of two ASK receivers utilizing bandpass filters to differentiate between the central frequencies of f1 and f2 signals. Depending on the decision generator, he will define weather the pulse is defined as a logical 1 or 0 based on the values of two envelope detectors. If the subtraction of the first and second envelope detector is bigger than 0, then the output will be defined as a logical 1 otherwise if it is equal or less than 0 it will be defined as a logical zero [4].

2.3.3. PSK Modulation

PSK is a modulation technique used in underwater acoustic communication systems to transmit digital data over long distances. In PSK modulation, the phase of the carrier wave is varied to represent the binary data. In BPSK, the phase of the carrier wave is shifted by 180 degrees to represent binary 0 or 1. In QPSK, the carrier wave is split into two orthogonal components, and the phase of each component is shifted to represent two bits of binary data at once. In differential PSK (DPSK), the phase shift between two consecutive bits is used to represent the binary data. PSK modulation is preferred in UWAC systems because it is less affected by the phase fluctuations caused by the water environment compared to other modulation techniques, such as amplitude modulation. Additionally, PSK can achieve higher data rates and better spectral efficiency compared to other modulation techniques [1].

2.3.4. Spread Spectrum Modulation

Spread spectrum modulation is a technique that increases the signal bandwidth to resist interference in the transmission process. The technique involves spreading the signal over a wide frequency range using an independent code order, which is achieved through coding and modulation. The receiver uses the same code to recover the transmitted information. Spread spectrum modulation is similar to conventional data communication, but with an added spreading processing step that expands the symbols to be transmitted with a feature code called code chips. The receiving end uses a despread process to restore the N code slices to one symbol [1].

3. UNDERWATER OPTICAL COMMUNICATIONS

Underwater optical communications (UWOC) is a rapidly developing field that involves the use of light to transmit data through the water medium. Compared to traditional acoustic communication, optical communication has several advantages, such as higher data rates, greater bandwidth, and lower latency. In UWOCs, the light source can be a laser or light-emitting diode (LED), which generates light in the visible or near-infrared spectrum. The light beam is then transmitted through the water medium to a receiver where it is detected and converted back into the original data. UWOC faces several challenges, such as absorption and scattering of light in the water medium, turbulence, and background noise. These factors can significantly degrade the signal quality, reducing the effective range and data rate of the communication system. The solution is usage of sever techniques such as wavelength division multiplexing, which allows multiple channels to be transmitted simultaneously over different wavelengths, and adaptive modulation and coding, which adjusts the modulation scheme and coding rate in response to changes in the channel conditions. Moreover, UWOC can be integrated with other communication modalities, such as acoustic communication and radio frequency communication, to provide a hybrid communication system that combines the advantages of each modality. Such hybrid systems can improve the reliability and data rate of underwater communication and enable a wide range of applications, such as underwater monitoring, environmental sensing, and oceanographic research [8].

3.2. FOUR TYPES OF OPTICAL UNDERWATER COMMUNICATION CONFIGURATIONS

Based on link configurations between the nodes in underwater wireless network, there are four different categories of UWOCs. Those are point-to-point line-of-sight (LOS), diffused LOS (DLOS), retroreflector-based LOS and NLOS (non-line-of-sight) configuration [1].

3.1.1. Point-to-point line-of-sight

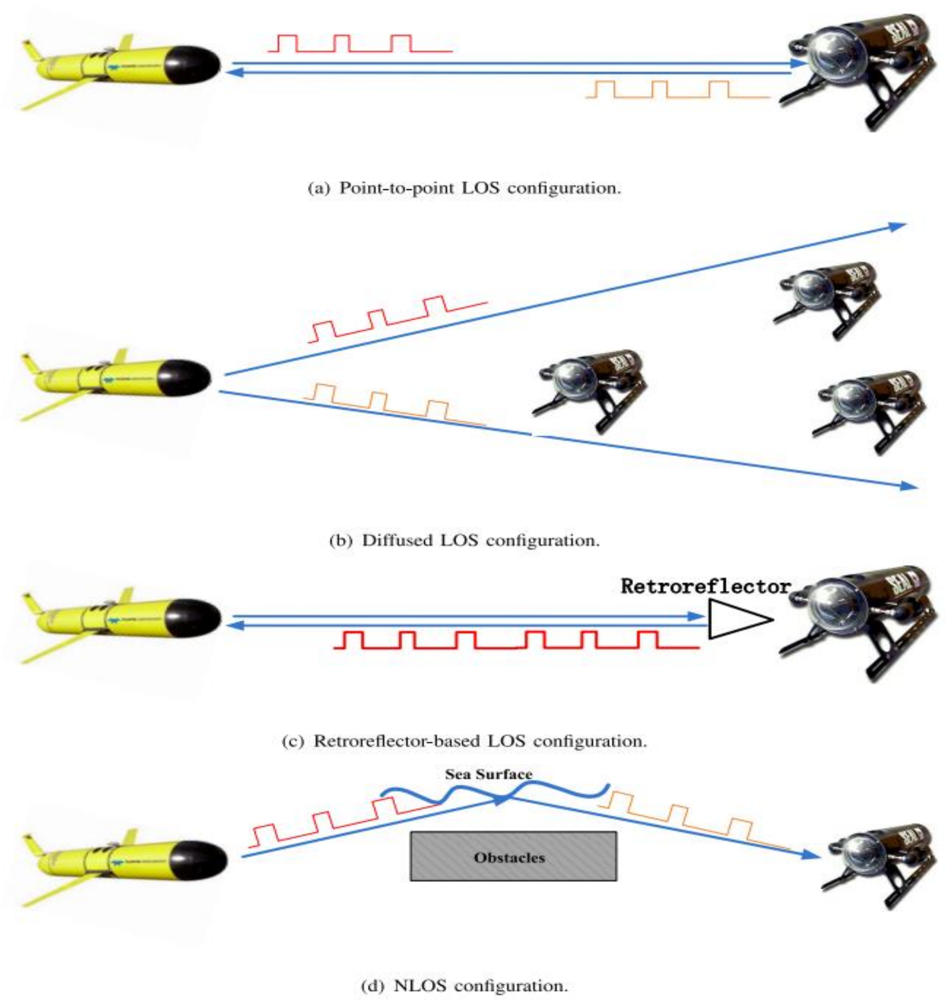
A point-to-point LOS is a that involves establishing a direct optical link between two underwater devices. This configuration is typically used for short-range communication over distances of up to a few hundred meters. The communication link in a point-to-point LOS configuration is established by aligning the optical transmitters and receivers of the two devices with each other. The devices must have a clear line-of-sight between them to ensure that the optical signal can be transmitted effectively. To achieve this, the devices may be placed on fixed underwater platforms or mobile vehicles that can maneuverer to maintain the line-of-sight connection. Point-to-point LOS provides a higher bandwidth, lower latency, and higher security due to the narrow beamwidth of the optical signal. However, the configuration is limited by the requirement for a clear line-of-sight between the devices, which can be affected by environmental factors such as water turbidity and attenuation [2].

3.1.2. Diffused line-of-sight

Diffused line-of-sight (DLOS) is a type of configuration that involves using a non-directional optical signal to establish a communication link between two devices. This configuration is typically used for short to medium-range communication over distances of up to several kilometres. In a DLOS configuration, the optical signal is transmitted in all directions from a central source, creating a diffused beam of light. This beam is then received by multiple receivers distributed over a wide area, allowing for the establishment of a communication link even in the absence of a clear line-of-sight between the devices. Advantages of DLOS include possibility to transmit to multiple points, transmitter and receiver do not need be perfectly aligned as in point-to-point LOS, low cost, and relatively simple construction. Limitations of DLOS include shorter communication ranges, lower data rates, high aquatic attenuation due to the large interaction area with water, severe multipath propagation, and low energy efficiency [2].

3.1.3. Retroreflector-based line-of-sight

The retroreflector-based line-of-sight (RLOS) configuration involves using retroreflectors to establish a direct communication link between two underwater devices. This configuration is typically used for short-range communication over distances of up to a few hundred meters and to put into effect full-duplex channels with restricted strength and size. In a RLOS configuration, a retroreflector is placed on the receiving device. The retroreflector reflects the incoming optical signal back to its source, creating a narrow beam of light that can be detected by the transmitting device. This allows for the establishment of a communication link even in the absence of a clear line-of-sight between the devices. Advantages of RLOS configuration are good efficiency, light and compact size of receiver and ability to use duplex channels [2].



(a) Point-to-point LOS configuration.

(b) Diffused LOS configuration.

(c) Retroreflector-based LOS configuration.

(d) NLOS configuration.

Figure 3 Four configurations of underwater network

Source: Zeng Z. et al.: *A Survey of Underwater Optical Wireless Communications,* IEEE Communication Surves & Tutorials, vol 19., issue 1., 2017., p. 204-238, online: https://ieeexplore.ieee.org/abstract/document/7593257

Disadvantages include the possibility of the reflected signal being disrupted by the backscatter of the transmitted signal causing high signal-to-noise ratio and bit-error rate and higher attenuation since the signal traverses the channel path twice upon transmission and reflection.

3.1.4. Non-line-of-sight

Non-line-of-sight (NLOS) underwater is used when the straightforward line-of-sight between the transmitting and receiving devices is obstructed. This configuration is typically used for communication over short to medium distances, where direct line of sight between the transmitters is not possible. In a NLOS configuration, the optical signal is reflected off surfaces such as the seabed, walls, or other objects in the water, to reach the receiving device.

This is achieved by using a wide beam of light that can reflect off multiple surfaces and reach the receiver from different directions. Main advantages of NLOS is low pointing and tracking requirement while disadvantages include high path loss, vulnerability to background radiation and possibility of sea surface slopes induced by wind or other sources, this will reflect the light back to transmitter and cause severe signal dispersion [2].

3.2. SYSTEM STRUCTURE OF UNDERWATER OPTICAL SYSTEM

An UWOC system typically consists of a transmitter, a receiver, optical source, and an optical channel that carries the signal between the two devices. The system may also include optical amplifiers or repeaters to boost the signal strength and extend the range of the communication link. The transmitter converts the electrical signal into an optical signal using a modulated light source such as a laser diode. The modulated signal is then sent into the water through an optical window, which is a material that allows the light to pass through but does not let water into the system. The receiver uses a photodetector to detect the incoming optical signal and convert it back into an electrical signal. The signal is then processed and demodulated to recover the original data transmitted by the transmitter. The receiver may also include amplifiers or filters to improve the signal quality and reduce noise [1].

3.2.1. Modulation

UWOC systems utilize two types of modulation techniques to encode data onto the optical signal: direct modulation and external modulation. Direct modulation involves controlling the current of the driving laser to achieve signal modulation, while outer modulators use an optical signal of consistent power emitted by the laser to achieve modulation. The two primary modulation techniques used in UWOC system optical terminals are intensity modulation and coherent modulation, with intensity modulation being the most widely used due to its simplicity and great power efficiency. The objective of modulation methods in UWOC systems is to improve their performance, and the appropriate technique depends on the specific performance requirements of the application scenario. Instances of situations may involve long-range communications under power limitations or sensors deployed underwater with finite battery power, photodetectors with restricted bandwidth in environments with multipath propagation, and murky or turbid media. In order to satisfy the demands of such situations, various modulation methods have been suggested, including On/Off Keying (OOK), pulse position modulation (PPM), as well as 2PSK, QPSK, and QAM." [1].

3.2.2. Coding

Researchers have proposed several UWOC coding techniques to counteract the effects of underwater fading. These techniques include low-density parity check, turbo, Reed-Solomon (RS), convolutional, and other channel coding schemes. The use of forward error correction (FEC) coding techniques is a common way to increase the energy efficiency, reliability, and distance of UWOC systems, but it comes at the cost of bandwidth [1]. FEC codes are made up of packet codes and convolutional codes, with packet codes being favoured due to their simplicity and ease of implementation. The commonly used packet codes include cyclic redundancy check codes, Bose-Chaudhuri-Hocquenghem codes, and RS codes. While packet codes are simple, they may not provide optimal performance, especially in highly turbid water. In such cases, more complex and powerful codes like turbo codes, which are combined codes generated by merging two or more convolutional codes, are used [1].

3.2.3. Light Source Technology

Light source technology is an aspect of UWOC systems, as it determines the system's data transmission capability and energy consumption. In recent years, advances in laser technology have provided UWOC with high-performance light sources capable of achieving high data rates and long-range transmission. The most commonly used lasers in UWOC systems are laser diodes (LD) and light-emitting diodes (LED). Compared to LEDs, LD emit light with a much narrower spectral width, this in turn allows higher data rates and longer transmission distances and reduces the effects of scattering and absorption in water which causes signal degradation. Another difference is the coherence of the emitted light. Laser diodes emit coherent light, which means that the light waves are in phase with each other and have a well-defined direction of propagation. This can be an advantage in underwater communications because it allows for the use of narrow beams that can be focused on a specific location. In contrast, LEDs emit incoherent light, which is less directional and spreads out in many directions, which in turn again causes higher signal attenuation and interferences. LEDs instead have less power consumption and cost less compared to LDs, which makes LEDs more dominantly used in battery operated systems. Additionally, semiconductor lasers, such as vertical-cavity surface-emitting lasers, have been used for short-range communications, as they are compact and can be modulated at high frequencies. In addition to laser technology, advances in optical fibers and waveguides have also contributed to the development of UWOC systems. Optical fibers can be used for transmitting light signals over long distances, while waveguides provide a means of transmitting light within a confined space[1] [10].

3.2.4. Signal Detection

The electronical component that detects optical signals in UWOCs is the photoelectric sensor, most common sensors are photo multiplier tube, photo intrinsic negative photodiode, and avalanche photodiode. For detection, several methods are used, direct detection, heterodyne detection, and homodyne detection. Direct detection is the simplest and most used method. It measures the received optical power and convert it into an electrical signal. However, direct detection has limited sensitivity and is not suitable for long-distance communication. Heterodyne detection is a more advanced method that involves mixing the received signal with a local oscillator to generate an intermediate frequency signal that can be detected more easily. This method provides higher sensitivity and better performance than direct detection, but it is more complex and expensive. Homodyne detection is similar to heterodyne detection, but it uses a local oscillator that is phase-locked to the transmitted signal. This method is more complex than direct detection but simpler than heterodyne detection. It provides good sensitivity and is suitable for long-distance communication.

3.3. MODELLING OF UNDERWATER OPTICAL SYSTEMS

Modeling is an essential tool in understanding the behaviour of UWOC systems. It aids to estimate the optical signal strength by taking into account various losses, such as attenuation, multipath, and turbulence, that occur as the signal propagates through the underwater channel. A comprehensive and accurate model incorporates system design parameters and enables a best fit for the underwater environment. This can help estimate range, data rate, and coverage angles under different environmental and optical component conditions. In UWOC attenuations can be categorized into two groups, one being line-of-sight attenuations and other being non-line-of-sight attenuations.

3.3.1. LOS Attenuations

Modelling of LOS The Beer-Lambert law is commonly used to model the configuration of LOS UWOC systems. However, this law assumes that all scattered photons are lost, which is not true. The Radiative Transfer Equation (RTE) is a more accurate model for aquatic optical attenuation in UWOC because it considers the effect of multiple scattering and light polarization. However, solving the RTE is difficult due to the complex equations involved. Some researchers have proposed analytical models to simplify the calculations, while others have used numerical methods such as the Monte Carlo simulation. Although the Monte Carlo simulation has certain drawbacks, it is a practical and robust method for ocean optic applications. Some researchers have also developed stochastic models to evaluate the spatial and temporal distribution of photons in UWOC links [1].

3.3.1.1. Absorption and Scattering

Absorption is a process of energy transfer from light energy into other forms, primarily heat and chemical energy while scattering is the interaction between photons and

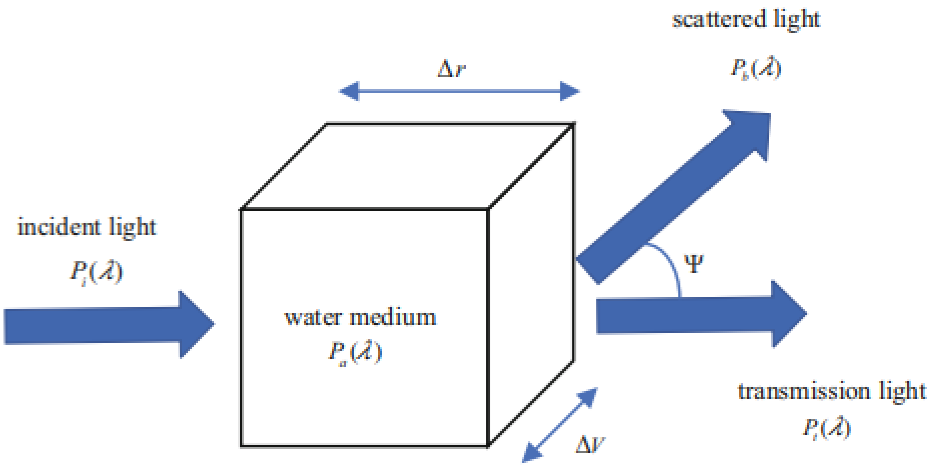


Figure 4 Graphical representation of light scattering

Source: Yi Lou, Niaz Ahmed, 2022, *Underwater Communications and Networks (Textbooks in Telecommunication Engineering)*, 1st edition, Springer Cham

molecules or atoms in the medium (in underwater communications water) and as a product will change the photon motion [1] [10].

3.3.1.2. Beer-Lambert Law

Beer-Lambert law, also known as Beer law, is a basic principle of spectroscopy that describes the absorption of light in a material. The law states that the amount of light absorbed by a material is directly proportional to the concentration of the absorbing species and the distance travelled by the light through the material. This relationship can be expressed as: $A = \varepsilon cl$ where A is the absorbance, ε is the molar absorptivity or extinction coefficient, c is the concentration of the absorbing species, and l is the path length of the light through the material. Beer-Lamber law evaluates the communication range and angle for different water types, main drawback is severe underestimation of received power due to scattering of photons [10].

3.3.1.3. RTE

RTE is used to model the propagation of light in an underwater environment and is used to predict the optical characteristics of the water. Equation itself is a set of integral-differential equations that describe how radiation energy propagates through a medium. It considers the absorption, scattering, and emission of radiation in the medium. In UWOC it is used to predict the received power, bit error rate, and channel capacity, main issue is the complexity of the equation [1].

3.3.1.4. Monte Carlo Simulation

Monte Carlo simulation is a computational technique employed to assess the probability distribution of a complex system or processes. The basic idea of simulation is to generate many random samples based on the probability distribution of the system, and then use these samples to estimate the behaviour of the system over time. This process involves generating a sequence of random numbers, each of which corresponds to a possible state of the system, and then using these numbers to simulate the behaviour of the system. With this method channel capacity for different link lengths, water types and transceiver parameters are considered [1].

3.3.1.4. Stochastic model

This method is used to model the random nature of optical beams as they propagate through the underwater channel. The stochastic model involves the use of statistical models to describe the random behaviour of the underwater environment, such as the scattering and absorption of light by the water and other particles present in the water. One commonly used statistical model for UWOCs is the Henyey-Greenstein (HG) function, which describes the angular distribution of scattered light. The HG function is used to model single scattering, non-scattering and multiple, scattering components of the underwater channel [1].

3.3.2. NLOS Attenuations

Modelling of the channel in a NLOS configuration is more intricate than that of a typical LOS configuration since it involves not only the attenuation effects, as in an LOS configuration, but also the back-reflection effect from the water-air interface. The NLOS path loss depends on several factors, including wavelength and device characteristics, as well as system geometry, such as transmitter beamwidth, communication range, receiver field of vision, and pointing elevation angles, and the optical properties of the underwater channel. Most of the models used to simulate the NLOS configuration rely on Monte Carlo simulations. Numerical results of the Monte Carlo simulation show that turbulence of underwater environment and random surface slopes degrade the overall quality of received signal, this is even more significant when the received signal has scattering of light particles [1].

4. UNDERWATER ELECTROMAGNETIC COMMUNICATIONS

Underwater electromagnetic (EM) communications is still in the process of research, concerns regarding the biological life in aquatic environments, such as the ocean and marine habitats, have intensified, leading to a need for new, cost-effective real-time monitoring systems [6]. The implementation of the Water Framework Directive across the European Union and increasing global attention on water quality management and sustainability have created a demand for intelligent underwater monitoring systems. Most underwater communication methods rely on acoustic or optical transmission. However, underwater acoustics have limited data rates due to low velocity and bandwidth limitations associated with operating frequencies. Moreover, in shallow water, the attenuation of underwater acoustics is prohibitively high, with challenges including multipath propagation, poor performance due to turbidity, ambient noise, and negative impacts on marine life. Similarly, optical communication is not practical in highly turbid environments. EM communication has not been considered for use in underwater environments due to attenuation at high frequencies. However, EM waves offer numerous benefits, including high propagation velocity (up to 3×10^7 m/s), greater bandwidth, higher data rates, and better transmission across boundaries such as air, water, seabed, and ice. The conductivity of seawater is approximately 4S/m, whereas freshwater is in the mS/m range. Freshwater attenuations are present in all three communication types, and represent a significant issue, although they typically are weaker compared to seawater attenuation due to lack of salinity, and weaker water turbulences [7].

4.1. EM WAVE PROPAGATION

4.1.1. Conductivity

The ability of an EM wave to propagate through a medium is influenced by the conductivity of the medium. When the conductivity of the medium increases, the transmitted signal is subject to greater attenuation, which can weaken the signal as it travels. This effect can be observed in seawater, which has a high average conductivity value that can vary depending on the physical properties and salinity of the water. It has been reported to be approximately 4 S/m. On the other hand, pure water has a lower average conductivity value, typically ranging from 0.005 to 0.01 S/m. For salinity of 38 ppt and temperature of 25°C which is the average value measured in Mediterranean Sea, conductivity is set to be 5.6 S/m [5].

4.1.2. Permeability and Permittivity

Relative permeability and permittivity of seawater affect the propagation and behaviour of EM waves in the underwater environment. The relative permeability of seawater is very close to that of vacuum, which means that it does not significantly affect the magnetic properties of the EM wave. In contrast, the relative permittivity, also known as dielectric constant in seawater, is much higher than that of vacuum, which means that it strongly affects the electric properties of the EM wave, relative permittivity is usually set to 81. It influenced by the concentration of dissolved ions and other impurities in the water. As the concentration of ions increases, the relative permittivity of seawater also increases, which can lead to a greater attenuation of the EM signal as it travels through the water. In addition, the high relative permittivity of seawater can cause significant reflection and refraction of the EM wave at the water-air interface, which can further complicate underwater communication and sensing [5].

4.1.3. Intrinsic Impedance

Intrinsic impedance of the seawater is a measure of the resistance that seawater presents to the propagation of EM waves. It is related to the relative permeability and permittivity of the seawater through a constant known as the wave impedance, which is given by the product of the square root of the relative permittivity and the relative permeability of the medium. It is affected by various factors, such as the salinity, temperature, and pressure of the water. Typically, the intrinsic impedance of seawater is reported to be around 120 Ω, which is higher than the intrinsic impedance of free space (approximately 377 Ω). This difference in impedance can cause significant reflection and refraction of the EM wave as it travels through the water, this affects the range and reliability of underwater communication and sensing [5].

4.1.4. Underwater Path Loss

Underwater path loss refers to the reduction in strength of EM waves as they propagate through water, in other words difference between send and received signal. Reduction in strength is triggered by a combination of absorption, scattering, and reflection of the waves as they travel. It can be described as $P_r = P_t + G_t + G_r - L$ where P_t stands for power of transmitted signal, G_t transmitter gains, G_r receiver gains, P_r power of received signal, and L for underwater path loss [5].

4.1.5. The Speed of Electromagnetic Wave Underwater

Velocity of EM waves underwater is generally slower than the velocity of light in vacuum (approximately 299 792 458 meters per second). Which is considerably more compared to UWAC for example, biggest flaw as mentioned before is the high attenuation rates. It is also worth mentioning that with speed of EM waves is proportionate with frequency EM waves, with lower frequencies 10Hz – 1Mhz speed drops down up to 75% of speed of light [5].

4.2. SYSTEM COMPONENETS OF EM COMMUNICATIONS

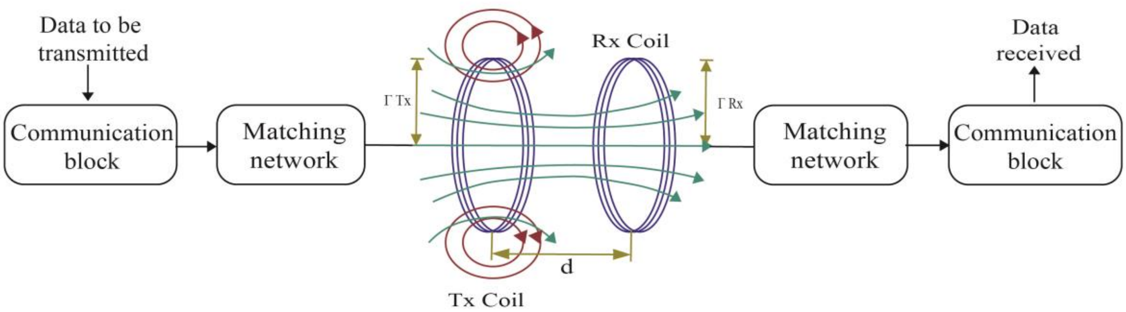


Figure 5 Block diagram of a typical EM communication system

Source: Made by the student in Adobe Illustrator

Main difference between EM systems and other ones is that EM systems receiver (Rx) has to be inside the magnetic field or „magnetic bubble“ generated by transmitting coil (Tx). This chapter will provide a simplified explanation of EM system [1].

4.2.1. Coils

Coils are used to generate and detect EM signals, thus making them the most important component of EM system. They are a simple copper or any conductive wire that is wound into a loop or a series of loops. In underwater EM communications they are used as antennas and as inductive couplers. An inductive coupler is a component that is used to transfer electrical power and/or information between two systems without physical contact. In this case they are used to transfer power and data between a surface buoy and an underwater device. As for serving as antennas, by having an alternative current present on the receiving coil, it creates a magnetic field which induces voltage and enables the detection of EM signal. A small form factor is an important consideration for designing an underwater EM antenna. Size is primarily influenced by the frequency of transmitted EM signals, with the increase in frequency the size of antenna decreases and vice versa [7]. Another factor that decides the size of the antenna is whether it is used in freshwater or seawater with former having a smaller size.

4.2.2. Matching Networks

Matching networks are used to maximize the transfer of power between different components of the system. It is essentially a circuit that matches the impedance of one component to the impedance of another component, to minimize the loss of energy that occurs when there is a mismatch between the two impedances, in this case, the matching network makes sure the impedance of the transmitting and receiving antennas match up. The impedance is configured using a combination of series and parallel LC combinations [1].

4.2.3. Communications blocks

Communication blocks in EM underwater communications are similar to those used in terrestrial communications, but they are designed and optimized for the unique challenges of the underwater environment. Implementation of a communication block is different for analog and digital signals. Variation with analogue signals is easier to implement since the value is constantly changing with time, most often represented by a sinusoidal signal. While digital signals without proper demodulation method can often misinterpret the signal especially if the signal has a value of “1” for prolonged period of time, for example a signal of value of 1110 would be defined as 10 on the receiving side, to prevent this the digital signal is often encoded with either forward error correction, Manchester or Manchester differential encodement. Most common modulation techniques include ASK, FSK and PSK [1].

5. UNDERWATER COMMUNICATIONS INDUSTRY EXAMPLES

Underwater communications found its application in numerous fields, from commerce, to science and military fields. From communicating between two submarines or between underwater vehicles and remote control stations, between sensors and surveillance systems to collecting data from underwater sensors, buoys, observatories, and even used to collect data for acoustic reasearch of marine mammals and other marine animals.

5.1. ACOUSTIC AND OPTICAL MODEMS

Acoustic and optical modems are two types of modems that are commonly used in communication systems. Both types of modems are designed to transmit and receive data signals over a communication channel. Acoustic modems use sound waves to transmit and receive data signals. Sound waves are produced by a transducer, which converts electrical signals into acoustic signals. The sound waves travel through the water and are received by the receiving modem. The receiving modem converts the sound waves back into electrical signals, which can be processed and interpreted by a computer. Optical modems on the other hand use light waves to transmit and receive data signals. Light waves are produced by a laser diode or an LED, which are then transmitted through an optical fiber. The light waves are received by a photodetector, which converts the light waves back into electrical signals. EM communications still do not exist yet,

5.1.1. BlueComm 200

BlueComm 200 is an example of an optical modem, it is designed by Sonardyne International Ltd. It uses an array of high-power LEDs that are rapidly modulated to transmit data. It uses a separate photomultiplier tube as its receiving element. The photomultiplier tube allows sensitive receive capability and communication ranges of up to 150 m. The system consists of a surface control unit, an underwater transceiver, and an optical cable. The transceiver is attached to the underwater device, and the optical cable connects the transceiver to the surface control unit. The control unit interfaces with the user's computer, providing a simple interface for data transmission. One of the main advantages of the BlueComm 200 system is its high data transmission rate. The system can transmit data at speeds of up to 10 Mbps.

5.1.2. EvoLogics S2C

The EvoLogics S2C R Series Acoustic Modems are a range of underwater communication systems developed by EvoLogics GmbH, a German company specializing in underwater communication and navigation technology. It uses a combination of frequency modulation and spread spectrum technology to provide reliable and secure communication in harsh underwater environments. The modems transmit and receive data using acoustic waves, with a range of up to 25 kilometres, making them suitable for long-range communication. The modem has a range of configurable options, including the transmission power, data rate, and modulation scheme. This enables the modems to be optimized for different communication scenarios, such as short-range communication in shallow water or long-range communication in deep water. It also features advanced error correction algorithms, which enable the modems to correct errors in the received data, resulting in reliable data transmission. The modems also have built-in diagnostic tools, which allow users to monitor the performance of the modem in real-time, making it easy to troubleshoot any issues that may arise.

5.2. UNDERWATER VEHICLES

5.2.1. Untethered Remotely Operated Vehicle

Untethered remotely operated vehicle (UROV) are unmanned underwater vehicles that operate autonomously or are controlled remotely by a human operator from a distance. Unlike tethered remotely operated vehicles (TROV), UROVs are not connected to the surface by cables or wires and are free to move around in the water. They are equipped with a range of sensors, cameras, and other instruments that allow them performance of tasks such as underwater inspection, maintenance, repair, deep-sea exploration, study of ocean currents, hydrothermal vents and other phenomena that occurs underwater. One example of UROV is Eelume, it is a modular vehicle, which combines thrusters, joints, sensors, and different payload modules. Sensors and tools can be mounted anywhere along the flexible body.

Figure 6 UROV Eelume

Source: Eelume Subsea Intervention, online: https://eelume.com/#the-story

By installing tooling at each end and shaping the vehicle body into a U-shape, a configuration with two arms is obtained. One of the arms is capable of grasping and stabilizing the vehicle, while the other arm can perform tasks related to inspection and intervention. Additionally, one of the arms can provide a camera view of the tool operation being performed by the other arm.

5.2.2. Tethered Remotely Operated Vehicles

TROVs compared to UROVs are linked to a surface vessel or platform by a long umbilical cord, which provides power, control, and communication between the ROV and the operator. The umbilical cord also serves as a tether, limiting the range of the vehicle and making it dependent on the surface support vessel or platform. One example of a tethered TROV is the SeaEye Falcon. The Falcon is a compact and versatile TROV that is designed for use in a variety of underwater environments, including offshore oil and gas, marine science, and defence. The vehicle is linked to the surface by a long, fibre-optic tether, which provides power, control, and video feedback to the operator. The Falcon TROV is equipped with high-resolution cameras, powerful LED lights, and a range of sensors and manipulators, making it capable of performing a wide range of tasks, including inspection, survey, and intervention. The Falcon TROV is also highly manoeuvrable, with six thrusters that allow it to move in any direction and maintain position in strong currents. SeaEye Falcon size is one metre long with weight of 60kg in air, and payload capacity of 14kg. being able to reach the depths of 1000m.

5.2.3. Hybrid Remotely Operated Vehicles

Hybrid remotely operated vehicle (HROV) is a vehicle that can operate either as TROV or UROV. One example of an HROV is HROV Nereus, it aids in a wide array of science procedures which are push coring, measuring heat flow, geotechnical and geochemical sensing, rock sampling and drilling, biological sampling, water sampling, high resolution acoustic bathymetry, and optical still and video imagery. On land it weights 2800kg with a payload capacity of 25kg, maximum speed is 3 knots, and it operates on rechargeable lithium-ion batteries with 15 kilowatt hours. Has multiple thrusters, 2 fore and aft, 2 verticals, and 1 lateral in remotely operated vehicle (ROV) mode and 2 fore and aft, and 1 vertical in autonomous underwater vehicle (AUV) mode. From sensors he is equipped with magnetometer and CTD which enables him to measure salinity, depth, electrical conductivity, temperature, and pressure of seawater. Scanning sonar with forward look and profile operating on 675 kilohertz and hydraulic manipulating arm to perform underwater operations. Nereus operates in two stages, first is the autonomous survey of the sea floor, where Nereus operates on a low bandwidth acoustic communication signal and positioning network.

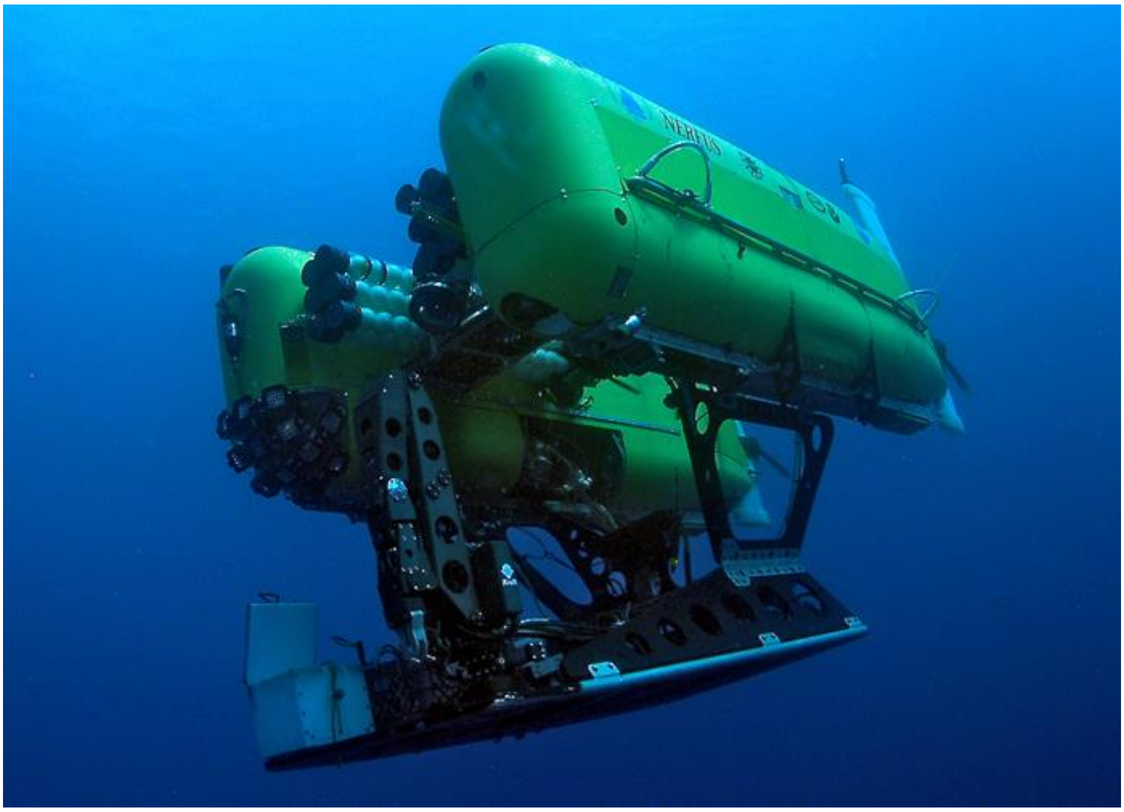


Figure 7 HROV Nereus

Source: HADES (HADal Ecosystem Studies), 2014, online: https://web.whoi.edu/hades/nereus

Once the research team finds a valuable sample, Nereus is tethered to the vessel via micro-thin, fiber-optic cable. Tether transmits high-quality, real-time video images and enables the pilot to collect said sample or conduct experiments.

5.2.4. Autonomously Operated Vehicles

Autonomously operated vehicles (AOVs) are robotic systems that are designed to operate underwater without the need for direct human control, and without the need for a tether. AOVs have several advantages over traditional manned vehicles, such as submarines and divers, they can operate for longer periods of time without the need for life support systems, which makes them more cost-effective and efficient, in other words they can also be deployed in hazardous environments or situations where human safety is a concern. Additionally, AOVs can collect data and perform tasks in a more systematic and repeatable manner than humans, which can improve the quality and accuracy of the data collected. One example of AOV is the SeaExplorer glider, developed by French company Alseamar. It is designed to collect oceanographic data, such as temperature, salinity, and currents. The glider can travel long distances up to 1700 kilometres to a depth of 1000 metres and has a battery life of 6 months.

Figure 8 SeaExplorer glider

Source: Ecomagazine, May/June 2020, online:
http://digital.ecomagazine.com/publication/?i=659148&article_id=3667939&view=articleBrowser

6. CONCLUSION

Underwater communications is an essential technology that has been developed to address the challenges of transmitting data and information in an underwater environment. Over the years, significant advancements have been made in this field, and various methods have been developed to improve the efficiency and reliability of underwater communication systems. Biggest challenge for underwater communications is the attenuation of signals due to the absorption, scattering, reflection and other phenomena that occurs underwater. UWAC enables the communication over longer distances, but with limited data rates. In other words, it does not provide sufficient bandwidth and response time for delicate operations but can be a reliable way of operation for AOVs while exploring the sea floor. Another flaw of UWAC compared to other communication method is the high noise levels caused by natural and human-made resources such as vessels, marine animals and even earthquakes. UWOC compared to AWAC offers higher data transmission rates, higher bandwidth, and lower latency. It provides reliable method of communication via optical-fibre for ROVs but is still lacking for wireless configurations which is heavily influenced by water turbidity, scattering and absorption of light, and in some cases limited by requirement of direct line-of-sight between transmitter and receiver. Underwater EM communications is still an active field of research, although it has the highest attenuation rates primarily caused by intrinsic impedance of seawater, it has a potential to become a communication method with highest bandwidth, and fastest data rates, and best transmission across different medium boundaries. Overall, the choice of underwater communication technology depends on the specific application requirements, and each technology has its advantages and disadvantages. With ongoing research and development in this field, we can expect to see further advancements in underwater communication technology, which will undoubtedly lead to significant improvements in various fields, including marine science, oceanography, and underwater robotics.

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LIST OF ABBREVATIONS

Abbrevation	Full name
AOV	Autonomously Operated Vehicles
ASK	Amplitude Shift Keying
BPSK	Binary Phase Shift Keying
DLOS	Diffused line-of-sight
DPSK	Differential Phase Shift Keying
EM	Electromagnetic
FEC	Forward Error Correction
FSK	Frequency Shift Keying
HG	Henyey-Greenstein
HROV	Hybrid Remotely Operated Vehicle
LD	Laser Diode
LED	Light-Emitting Diode
LOS	Line-of-sight

NLOS	Non-line-of-sight
OFDM	Orthogonal frequncy-division multiplexing
OOK	On/Off Keying
PPM	Pulse Position Modulation
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RLOS	Retroflector-based line-of-sight
RTE	Radiative Transfer Equation
RS	Reed-Solomon
SSB	Single Sideband
TROV	Tethered Remotely Operated Vehicle
UROV	Untethered Remotely Operated Vehicle
UWAC	Underwater Acoustic Communication
UWC	Underwater Communication
UWOC	Underwater Optical Communication

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