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colour inside

Internet of things (IoT) – Underwater communication technologies for IoT

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INTERNET OF THINGS (IoT) –
UNDERWATER COMMUNICATION TECHNOLOGIES FOR IoT

FOREWORD

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The text of this Technical Report is based on the following documents:

DTR	Report on voting
JTC1-SC41/183/DTR	JTC1-SC41/203A/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1, available at www.iec.ch/members_experts/refdocs and www.iso.org/directives.

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INTRODUCTION

Earth is the aquatic planet as water covers 70 % of its surface. Due to the rapid growth of technology, underwater communication technologies can be used for the development of various smart underwater applications. The underwater communication system is one of the fastest-growing fields since many applications such as monitoring applications, military applications, security applications, new resource exploration, etc. are continuously being developed and used. However, many applications still need to be studied in-depth and underwater resources also need to be explored. Therefore, the research in underwater communication technology plays a vital role in the exploration of undersea resources and the development of various underwater applications.

Using the radio frequency (RF) signal, the communication technology in the underwater environment can be extremely influenced by various factors such as environmental noise, pollution, power, etc. This can cause several issues related to attenuation, frequency fading, Doppler shift, multipath effect, etc. Hence, acoustic communication technology has been used by numerous researchers to solve these issues. In the case of high-speed acoustic communication, problems like limited bandwidth, reliability in data, error rate, multipath, etc. remain to be solved.

Optical communication technology is used for high-speed and short-range communication in the underwater environment. The optical communication uses the laser to carry the information through the water. In the case of long-distance communication in the underwater environment, optical communication is not suitable. The magnetic fusion communication in the underwater environment is only used for near-field communication. Therefore, all communication technologies are essential for underwater communication.

The purpose of this document is to provide a technical overview of the different communication technologies in the underwater environment such as acoustic communication, optical communication, Very Low Frequency (VLF)/Extremely Low Frequency (ELF) communication, and Magnetic Fusion Communication (MFC). Correspondingly, this document also provides the characteristics of each communication technology in the underwater environment, trends of underwater communication technology, layered design of underwater technology, and the application development using different communication technologies.

INTERNET OF THINGS (IoT) – UNDERWATER COMMUNICATION TECHNOLOGIES FOR IoT

1 Scope

This document describes the enabling and driving technologies of underwater communication such as acoustic communication, optical communication, Very Low Frequency (VLF)/Extremely Low Frequency (ELF) communication, and Magnetic Fusion Communication (MFC). This document also highlights:

- technical overview of different communication technologies;
- characteristics of different communication technologies;
- trends of different communication technologies;
- applications of each communication technology;
- benefits and challenges of each communication technology.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

4 Symbols and abbreviated terms

ACPG	a specific graph technique
AUV	autonomous underwater vehicle
ASK	amplitude shift keying
BER	bit error rate
BPSK	binary phase-shift keying
CBC-MAC	cipher block chaining-message authentication code
CCM-UW	counter with CBC-MAC for underwater
CRC	cyclic redundancy code
DTN	delay/disruption tolerant network
ELF	Extremely Low Frequency
FSK	frequency-shift keying
FSO	free space optics
HF	high frequency
IM	intensity modulation

ISI	inter symbol interference
ITU-R	International Telecommunication Union radio-communication
LED	light-emitting diode
LSI	large scale integration
LSB	least significant bit
MAC	medium access control
MANET	mobile ad hoc network
MFAN	magnetic field area network
MIMO	multiple-input and multiple-output
MSB	most significant bit
MSK	minimum shift keying
NRZ	non-return-to-zero
NRZ-L	non-return-to-zero level
OFDM	orthogonal frequency division multiplexing
OOK	on-off keying
OOK/CWK	on-off keying/continuous wave keying
PSK	phase-shift keying
RF	radio frequency
RTT	round trip time
RZ	return to zero
SHELF	super hard ELF system
SLF	super low frequency
SNR	signal to noise ratio
SONAR	sound and navigation and ranging
TDMA	time division multiple access
UAN	underwater acoustic network
ULF	ultra-low frequency
UUV	unmanned underwater vehicle
UWA MAC	underwater acoustic MAC layer
UWASN	underwater acoustic sensor network
VBF	vector-based forwarding
VLF	Very Low Frequency
WDM	wavelength division multiplexing
WSN	wireless sensor network

5 Enabling/driving technologies of underwater communication

5.1 General

Various enabling/driving technologies of underwater communication such as acoustic communication, optical communication, Very Low Frequency (VLF)/Extremely Low Frequency (ELF) communication, and Magnetic Fusion Communication (MFC) are discussed in Clause 5.

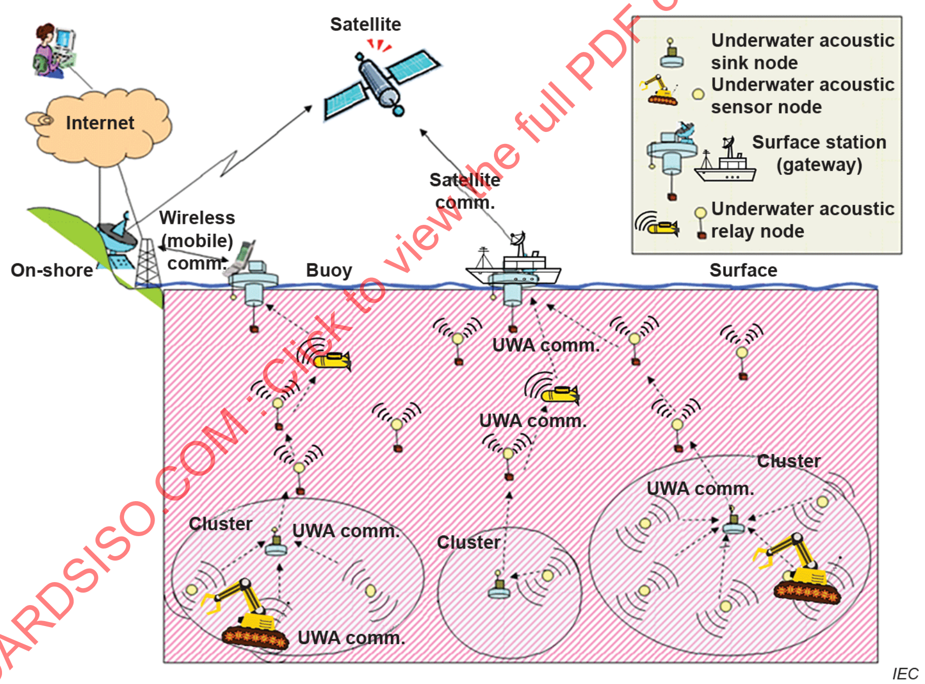
5.2 Acoustic communication

5.2.1 Technical overview

5.2.1.1 Technical definition

Underwater acoustic communication is a technology to transmit information wirelessly in the underwater environment using sound or ultrasonic waves. It includes underwater acoustic modem hardware and software, underwater acoustic communication protocol, underwater acoustic communication network, underwater application and service technology, etc. For decades, point-to-point communication technologies between two devices in water have been dominantly investigated, but quite recently, underwater acoustic network systems in which several underwater devices participate in information exchange have been studied.

Figure 1 is a conceptual diagram of underwater acoustic sensor network systems, which is one of the representative examples of underwater acoustic communication technology [1] [1]. Underwater acoustic sensor network system consists of underwater sensor nodes that collect information using underwater sensors, an underwater sink node that controls underwater sensor nodes located in a cluster, and a water surface gateway, which connects underwater network to terrestrial network. The main subjects of research and development are the technologies to improve the overall efficiency and stability of the underwater acoustic communication system and to increase communication speed and reliability between entities that constitute the system.



SOURCE: Kim Y. A Query Result Merging Scheme for Providing Energy Efficiency in Underwater Sensor Networks. Sensors. 2011, 11, pp. 11833-11855. Reproduced with permission.

Figure 1 – Example of underwater acoustic sensor network system

1 Numbers in square brackets refer to the Bibliography.

5.2.1.2 Characteristics of underwater acoustic channel

5.2.1.2.1 Definition and characteristics of sound wave

A wave is a physical phenomenon whereby periodic vibrations generated by an object are transmitted through a medium. In this case, the time from crest to crest is called period and the inverse of the period is called frequency. Technically, when the frequency of a wave corresponds to 20 Hz to 20 kHz, since the human ear can hear it, it is classified as an acoustic wave (sound wave). When the frequency of a wave is larger than 20 kHz, it is classified as an ultrasonic wave. Sometimes, both sound and ultrasonic waves are referred to as sound waves in a broad sense.

The sound wave is a longitudinal wave where the wave and vibration of the medium are in the same direction. Further, it only propagates through a medium such as gas, liquid, or solid. Also, the speed of the sound wave differs depending on the medium: 340 m/s in air, 1 500 m/s in the underwater environment, and 5 120 m/s in iron.

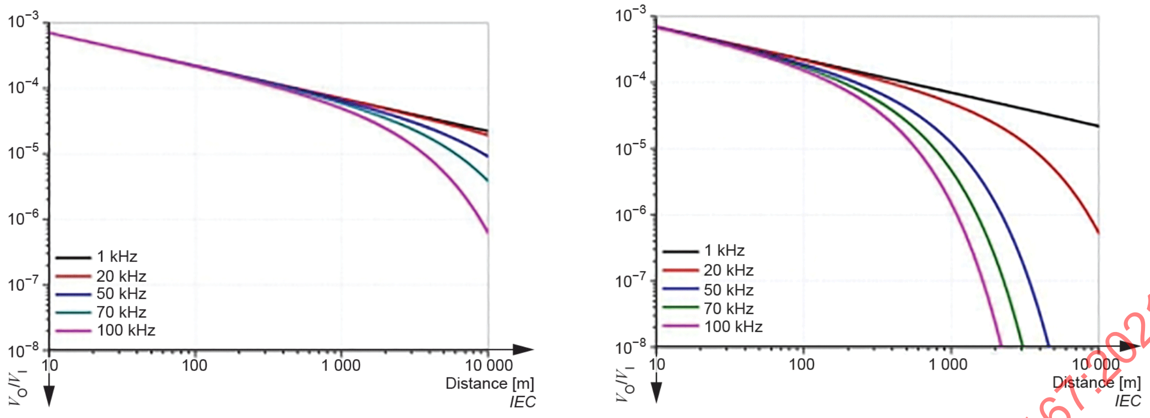
5.2.1.2.2 Transmission characteristics of sound wave in water

The media that can transmit information wirelessly in the underwater environment are radio waves, light waves, and sound waves. Among them, the radio wave is advantageous in that it is easy to design a transmission protocol due to its short propagation delay and to send high-speed data by utilizing a wide bandwidth. But due to the high conductivity in water, the transmitted signal is rapidly attenuated and communication distance becomes restricted. The light wave is characterized by its wavelength or its frequency, in this situation it supports very high-speed data transfer using ultra-wideband, but it requires a line of sight path between transceivers and is vulnerable to turbidity. Unlike radio wave or light wave, which is a kind of electromagnetic wave, the sound wave attenuates slowly in water ensuring communication distance of several tens of kilometres. Its main drawbacks are the low data rate and the long propagation delay due to narrow bandwidth and the underwater medium, respectively. Underwater data transmission technique using sound wave has been widely used for the past several decades and its performance and functions are verified in various aspects [2].

Sound velocity, which is the speed of sound waves used in water, changes due to water temperature, salinity, and water pressure. Specifically, the velocity of sound increases with an increase in water temperature, salinity, and water pressure. In general, an increment of water temperature of 1 °C causes an increase of the sound velocity of 4 m/s, an increment of salinity of 1 ‰ causes an increase of the sound velocity of 1,4 m/s, and an increment of 1 km in depth causes an increase of the sound velocity of 17 m/s [3]. On the other hand, there is a thermocline layer in which the water temperature decreases rapidly as the water depth increases in the area ranging from the water surface to hundreds of metres in depth. In the thermocline, the sound velocity decreases as the water depth increases due to the rapid decrease of the water temperature. Meanwhile, in the region where the water depth is deeper than the thermocline, the sound velocity tends to increase gradually with the increase of water depth since the water temperature is almost constant and the salinity and water pressure gradually increase [4].

The sound wave radiated in water undergoes path loss depending on the distance and the frequency, and the path loss can be divided again into two factors: spreading loss and absorption loss.

When it comes to spreading loss, the intensity of sound wave decreases in proportion to the distance in shallow water and in proportion to the square of the distance in deep water [5]. Absorption loss increases rapidly with increasing frequency and depends on salinity and water temperature partly. Figure 2 shows the ratio of received voltage to transmitted voltage (V_O/V_I) according to distance and frequency in (a) fresh water and (b) seawater. From Figure 2, it is observed that the path loss increases greatly as distance, frequency, and salinity increase [6].

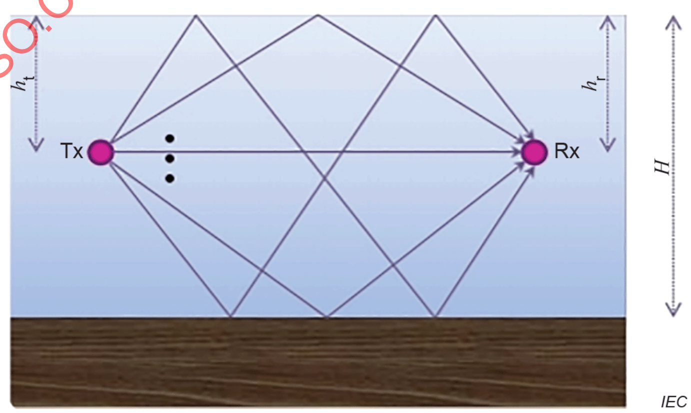


a) b)

Figure 2 – Path loss of sound wave

The sound wave in water is affected by noise, which can be classified into ambient noise and site-specific noise. Ambient noise generated by turbulence, waves, ships, etc. is always present in all locations and can be modelled as a Gaussian distribution. Its power spectrum density decreases by 18 dB when frequency increases by ten times [7]. On the other hand, the site-specific noise is irregular depending on the place, such as the icebreaking noise in the polar region and the snapping shrimp in the warm water region.

Another transfer characteristic of the underwater sound wave is reflected. As shown in Figure 3, the transmitted sound wave generates numerous paths due to the water surface and bottom [6]. The reflection coefficient of the water surface is theoretically "−1", which means that only the phase is inverted. The reflection coefficient at the bottom greatly depends on the medium, roughness, and grazing angle. Also, each sound ray experiences the phenomenon in which the sound wave refracts to the direction having a lower speed of a sound wave due to Snell's law. Another factor that distracts the transmission and reception of sound waves is the time-variant characteristic of the multipath. In other words, each path between transceivers can be changed drastically due to the movement of aquatic organisms, irregular water flow from underwater eddies, and irregular changes in wave height from the wind on the water surface.



Key

H water depth

h_t depth of transmitter

h_r depth of receiver

Figure 3 – Multipath of sound wave

The last issue to be addressed concerning the characteristics of the underwater sound wave is the Doppler effect caused by not only the intentional movement of the transmitter or receiver but also the drift of the transceiver due to waves, currents, and tides. The Doppler spread is proportional to the moving speed of the transceiver divided by sound velocity. As described above, since the sound velocity is very low in the water, small-scale movement generates a large Doppler effect.

5.2.1.3 Background

The origin of underwater acoustic communication technology is SONAR. SONAR is a technology that detects the position of an object by using a sound wave in water and there has been rapid progress of technology through two world wars. In detail, active SONAR detects the position of an underwater object by measuring the turnaround time between source and destination, whereas passive SONAR detects an object by listening and analysing the sound source by using a hydrophone. The progress of SONAR technology has catalysed the research and development of underwater acoustic communication system technology. In the early 1990s, the interest in a mid- and long-range point-to-point underwater acoustic communication system had increased throughout the world, especially centred on the US and Europe, which provides the communication distance of 1 km to 20 km for marine petroleum exploration, underwater robot control, marine structure construction and unmanned underwater vehicle operation. To meet this trend, the mid- and long-range underwater acoustic communication modem that has been commercialized forms the mainstream of the market related to the underwater acoustic communication system.

Meanwhile, since the 2000s, the importance of short-range underwater acoustic sensor network system which can provide various application services has been highlighted. Research on underwater acoustic communication modem and system technologies for the underwater acoustic network is continuously being expanded.

5.2.1.4 Technology classification

5.2.1.4.1 Underwater acoustic modem technology

The underwater acoustic modem is an integrated technology for designing and manufacturing (a) a digital part in which underwater acoustic access functions are implemented, (b) an analogue part composed of a passband filter and an amplifier, and (c) an acoustic transducer.

5.2.1.4.2 Physical layer technology for underwater acoustic communication

Physical layer technology for underwater acoustic communication includes a frame structure, modulation and channel coding, and detection technique which are suitable for data transfer in an underwater acoustic channel. This technology is aimed at the improvement of the efficiency and reliability of underwater communication.

5.2.1.4.3 Data link layer technology for underwater acoustic communication

Data link layer technology for underwater acoustic communication is a technology for efficiently using a limited underwater acoustic channel resource. It includes a medium access control technique to overcome long propagation delay of underwater sound waves.

5.2.1.4.4 UWA MAC technology for mobility support

This is a lower layer technology of MANET for mobility support as a technology required to support the dynamic connection of UWA communication link according to the underwater mobility of mobile UWA nodes such as AUV and UUV or submarines. Unlike terrestrial RF-based communications, long propagation delay, unstable time-variant underwater channel characteristics, low data transfer rates, and energy efficiency should be considered.

5.2.1.4.5 Security technology

The security technology of terrestrial RF-based communication cannot be directly applied to UWA communication due to the characteristics of an underwater sound wave channel such as the long propagation delay, high error rate, and low transfer rate of underwater acoustic communication. Therefore, this technology requires weight lightening in encryption keys, encryption/decryption algorithms, and security protocols to reduce the processing time and frequent communication in consideration of inherent characteristics of an underwater acoustic wave channel, high energy consumption, and low-performance hardware characteristics.

5.2.1.4.6 UWA communication network technology

Due to the characteristics of the underwater acoustic wave channel, as described above, the existing RF-based network schemes cannot be directly applied to the UWA communication network. Unlike RF-based routing, the UWA communication network needs to minimize propagation delays and transmission delays and to support the mobility of UWA nodes with the improvement of energy efficiency.

5.2.1.4.7 Cross-layer technology

This is a technology that allows one layer to use the information of another layer in the protocol stack, and it should consider characteristics in UWA communication and network. For example, UWA application layer information such as underwater temperature, salinity, water pressure, and depth information by underwater sensors can be used to control the data rate of UWA MAC or set the shortest distance route in UWA network layer. The location information of the neighbouring node is used to calculate the distance to the UWA node, and the UWA physical layer in the UWA MAC can adaptively control the energy consumption by transmitting the message with the appropriate transmission energy suitable for the distance between two nodes. By using cross-layer, it is possible to achieve energy efficiency, reduce end-to-end propagation delay, control QoS, provide and enhance layer functionality and performance. Besides, cross-layer technology has advantages in that similar information generations between layers and similar function code redundancy can be eliminated.

5.2.1.4.8 UWA DTN technology

DTN is a technology in which when the data packet is not forwarded to the destination node due to communication instability, the node saves the packets and retransmits when communication becomes stable again. This technology is used for reducing the packet loss and energy consumption. In UWA communication networks, unlike conventional RF-based communications, the research and development on this technology need to consider the specific characteristics of underwater acoustic communication channel focusing on high delivery ratio, short average end-to-end delay, and low energy consumption.

5.2.1.4.9 UWA MANET technology

UWA MANET refers to a network that supports dynamic routing paths depending on the movement of the UWA node in the underwater environment. The UWA node mobility makes the UWA communication link frequently disconnect from the existing neighbour node or connect to a new neighbour node. The existing terrestrial MANET technology cannot be applied to UWA MANET because of the characteristics of the underwater acoustic wave channel. Therefore, the UWA MANET technology needs to solve dynamic routing problems caused by very long propagation delays, very low data rates, very small packet sizes, and the frequent rerouting with its severe overheads due to mobility.

The UWA MANET which uses only UWA communication has a limit in real-time heavy traffic applications such as video stream transmission. To overcome this limitation, it is important to develop a technology for interworking with other kinds of underwater communication technologies such as optical wire/wireless technology and MFAN.

5.2.1.4.10 Terrestrial/underwater synchronization gateway technology

As shown in Figure 4, underwater data collected in the water eventually should be transmitted to terrestrial and, if necessary, command messages or data to control UWA nodes should also be transmitted from the terrestrial to underwater [8]. Unlike common interworking in terrestrial RF-based communication network, interworking between terrestrial and underwater communications can cause serious issues such as bottlenecks, data loss, communication delays, packet size mismatches, synchronization failures and routing failures due to the big difference in communication characteristics such as operating environment, communication medium, propagation delay, frequency bandwidth, transmission speed, bit error rate, etc. To solve these problems or minimize their extent, it is important to identify and reflect the internetworking problems between two different networks caused by the characteristics of underwater acoustic communication.

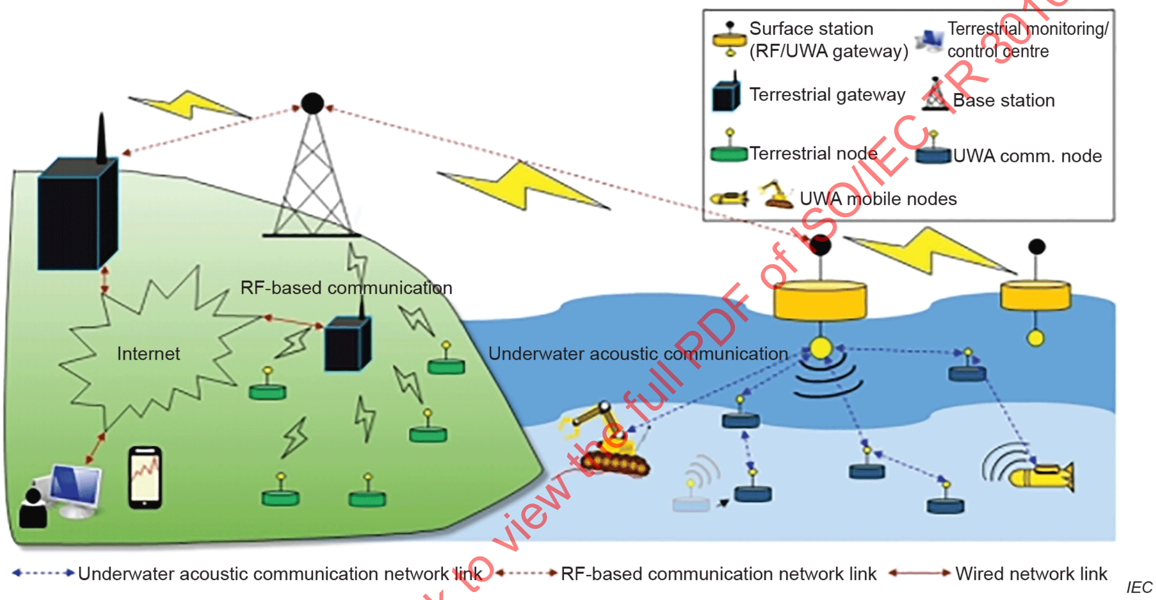


Figure 4 – Terrestrial/underwater interworking gateway

5.2.1.4.11 3D UWA location-awareness technology

Similar to the terrestrial area, location-awareness under the water can be used for numerous applications such as underwater navigation, underwater object or area location awareness, location-range based underwater information search, location-area based UWA node control and management, location-based monitoring, prediction of changes in specific areas or objects in aquatic environment changes, and others. Location information is also very useful for minimal cost communication linking and routing. Location-awareness is very useful for intelligent functionality and the performance of UWA MAC or UWA communication networks.

Unlike the terrestrial environment, in the underwater environment, 3D awareness technology is required including depth information. The problem is that the terrestrial location-awareness uses radio wave communication but the UWA location-awareness should use UWA communication. Here, there are serious obstacles in location-awareness performance such as long propagation delay, severe multipath problem, and the severe change of sound wave velocity due to time-variant changes in the underwater environments. The UWA 3D technology location-awareness should overcome those obstacles and improve the speed, accuracy, energy efficiency, and stability for location-awareness.

5.2.1.4.12 UWASN technology

UWASN technology is a UWA network application technology that uses UWA communication. As shown in Figure 1, the UWASN consists of UWA sensor nodes, UWA sink nodes, UWA relay nodes, and a surface station. Each UWA sensor node senses underwater objects or environmental conditions through one or more mounted underwater sensors and transmits the sensed data to the terrestrial centre via the UWA sink node, relay node, and surface station. The user command message is transmitted from the terrestrial centre to one or more UWA sensor nodes via the reverse path of this process. Through command messages, it is possible to control UWA nodes and operate the actuator attached to the node.

Related to UWASN technology, technologies on the UWA modem, PHY layer, UWA MAC layer, UWA routing, UWASN architecture, and application services have been developed up to now.

5.2.2 Trend of technology (modern communication trends)

5.2.2.1 Underwater acoustic modem technology

The underwater acoustic modem that provides the long communication distance has already been commercialized as various products after technical stabilization steps. Since the communication distance is increased as the used frequency is lower, which is the characteristic of underwater acoustic communication, the mid- and long-range underwater acoustic modems supporting the communication distance of several kilometres are mainly implemented using the frequencies within 30 kHz [9].

On the other hand, short-range underwater acoustic modems are in the introduction and growth stages of technology. Currently, prototypes equipped with various standards and technologies are designed, manufactured, and verified mainly in academia and research institutes. In short-range underwater acoustic modem technology, instead of limiting the communication distance to within 1 km, by communicating using frequencies of up to 100 kHz (or more), it is possible to reduce the size of the underwater modem. Also, development is in the process of equipping highly efficient physical layer transmission technology to provide improved data rates.

5.2.2.2 Physical layer technology for underwater acoustic communication

To perform stable and efficient communication using sound waves in water, it is essential to study the physical layer transmission technology considering the transfer characteristics of underwater sound waves.

Generally, entities participating in the underwater environment acoustic communication systems depend on built-in batteries and should be able to be driven for a long time without replacing batteries. Further, the data generated and transmitted by them have intermittent characteristics. That is, in the frame-based underwater acoustic communication, a preamble should be transmitted and received before the main data transmission and the receiver should acquire the starting point of each frame. Accordingly, various studies are being made on a preamble design and detection technique that makes it easy to detect a frame while using a short length.

The acoustic signal transmitted in the water experiences distortion due to the variability in time and frequency of the underwater channel. To overcome the physical obstacle of the underwater channel and to ensure proper communication quality, pilot symbols are commonly utilized. That is, based on the predetermined data sent from the transmitter, the receiver estimates the characteristics of the channel. In this regard, integrated research and development are being conducted such as pilot sequence design, pilot symbol allocation, and channel estimation algorithms which are optimized for the structure and requirements of various underwater acoustic communication systems.

To minimize the power consumption of underwater nodes and improve communication quality, it is important to design a physical layer frame optimally. That is, by selectively using the fields that are essentially required in the frame configuration of the physical layer, the transmitted frame is less influenced by the change of the underwater acoustic channel and the transmission efficiency could be improved.

Various physical layer technologies applied to data to be loaded in each physical layer frame are actively being studied. Among them, a modulation technique is a representative example. In the past, research has been mainly focused on the use of binary modulation such as PSK and FSK. However, in recent years, various researches on the application of acoustic communication have been carried out, for example, a high-order modulation technique for transmitting a plurality of bits to a modulation symbol and a multicarrier modulation technique for improving the efficiency and reliability of data transmission using a plurality of channels such as OFDM. Also, studies on channel coding and MIMO for the application of underwater acoustic communication are being studied.

5.2.2.3 Data link layer technology for underwater acoustic communication

The speed of sound waves in water is about 1 500 m/s, which is 200 000 times slower than that of radio waves commonly used in terrestrial communications. To overcome the distortion and entanglement of each transmitted frame, a delay-tolerant medium access control (delay tolerant MAC) technique is actively studied.

Since the bandwidth in which sound waves can be used in the water is limited to a maximum of several tens of kilohertz, it is very important to divide it into a plurality of channels and to allocate channels to users efficiently. In particular, since OFDM generates a large number of communication resources on the time and frequency axes, the importance of scheduling technology for distributing available resources in consideration of the underwater channel characteristics is increasing.

The function of data link layer for underwater acoustic communication is to interface with the network layer and physical layer and to form and manage frames. Therefore, based on the analysis of the characteristics of the underwater acoustic communication system to be constructed, techniques for optimizing message types exchanged with other layers and frame structure constituting MAC frames are studied with great importance to improve the efficiency of the system.

5.2.2.4 UWA communication network technology

UWA communication network technology has been developed focusing on the UWASN which has energy efficiency, short propagation delay, and mobility support routing technology. Routing schemes in UWASN can be mostly classified into the routing using location information, the routing focusing on energy efficiency, the routing to reduce propagation delay, the routing with mobility support, and the adaptive intelligent routing using dynamic environment information due to time-variant underwater environment change.

Location-based routing techniques have been introduced in many UWA routing protocols. In these routing protocols, UWA node location information is very useful for getting energy efficiency, short propagation delay, or mobility support. Depth-based routing (DBR), depth-based multi-hop routing (DBMR), sector-based routing, and VBF routing belong to this scheme [10], [11], [12], [13].

Several energy-efficient routing protocols have been introduced to overcome the drawback that UWA communication networks consume energy much more than terrestrial RF-based networks. As described above, technologies that reduce energy consumption by reducing unnecessary hops and data flooding with the location information and depth information of the UWA node have been introduced [10], [11], [14]. Methods to use AUV to support energy efficiency have also been proposed [15], [16], [17].

As the schemes for reducing the propagation delay, hybrid routing schemes and processing time reduction schemes have been proposed, where the hybrid routing schemes use both of RF-based communication and UWA communication and the processing time reduction schemes reduce the processing time in routing discovery and packet transmission [18], [19], [20], [21]. Most of the location-based routing schemes are also the very methods for reduci ng the propagation delay.

Routing protocols for mobility support perform route recovery and maintenance using location information, link quality, and multi-hop transmission schemes. HydroCast [22], DFR [23], and REBAR [24] were proposed as mobility support routing schemes.

Many intelligent routing protocols have been proposed in terrestrial communication networks and these protocols are based on learning such as fuzzy logic, neural networks, reinforcement learning, genetic algorithms, simulated annealing, and optimization techniques. These intelligent protocols, however, cannot be used for UWA communication other than fuzzy logic because of the characteristics of UWA communication. To actively support higher energy efficiency, shorter propagation delay, higher mobility, and stability in UWA communication networks in highly time-variant and unstable underwater environments, routing techniques that are intelligently adaptable to the underwater environment are essential to UWA communication networks.

5.2.2.5 DTN technology

DTN technology has been developed to achieve one or more of high delivery ratios, average end-to-end delay, and low energy consumption [25]. Since there are trade-offs between these metrics, it is very difficult to develop DTN protocol technology that satisfies all of them simultaneously.

The current proposed DTN techniques have been proposed based on terrestrial wireless networks. There are two types of extreme technologies: multiple replication method and single copy method. While multiple replication method broadcasts packets to all neighbouring nodes to pass them over multiple paths to the destination node [26], a single copy method sends just a message to the destination via only one route by sending it to only one neighbour [27].

The multiple replication method has the energy consumption problem, even though it has a high propagation rate and a short average end-to-end delay. On the other hand, a single copy method can reduce energy consumption, but the average end-to-end delay can be longer and the delivery rate can be lower. As a result, terrestrial wireless DTN studies have been conducted to reduce the energy consumption overhead while lowering the average end-to-end delay with a minimum number of packets and increasing the transmission rate.

One of the methods reliable in the UWA communication networks is the Delay-Tolerant Data Dolphin [15] scheme. In this scheme, Dolphin is a mobile UWA node such as AUV or UUV with sufficient memory and energy. It visits the area of stationary UWA nodes and collects data from each node in the area at close range. Then, it transmits the data to the surface station. This scheme has the advantage of reducing the energy consumption of the UWA node through short-distance communication with Dolphin. However, this method has the problem that the average end-to-end delay is increased and the transmission rate is lowered in the case that the UWA nodes in shadow areas where Dolphin does not visit frequently have less opportunity to transmit their stored data.

In the underwater routing, the UWA DTN scheme to route messages based on symmetric links has also been proposed [28], where asymmetric link refers to the link that can feed back packets to each other between two neighbour nodes. The symmetric link is more stable than the asymmetric link so that the message can be fed back to the previous node in case of communication failure. This protocol can reduce battery power consumption because there is no need to re-search the already linked nodes for reroute; however, if the node is added or deleted frequently, the battery power consumption may increase because the node re-search is needed.

A scheme that makes it possible to get an advantageous trade-off between data rate, propagation delay, and energy efficiency has been proposed [29]. In this scheme, each UWA node periodically exchanges information such as packet generation time, node time-space density, and residual energy. At that time, it determines transmission priorities between data packets and routes the data packets according to the priorities. This method can show good performance in energy consumption and packet delivery, especially, at frequent link failure occurrences, but if the mobility is low, there is a possibility that the packet priority is unchanged and the UWA node requires a large buffer space because it needs to keep a copy of the packet.

A method to find an optimized path with a specific graph technique (ACPG) that uses both of the single copy method and the stored movement pattern of a UWA node has also been proposed [30]. This technique uses a single copy delivery method to lower the communication overhead but requires a large memory to store the graph results [25].

A prediction-based DTN scheme has also been proposed [31]. In the architecture of this scheme, the cluster header works as a UWA sink node in the cluster-based architecture. If the cluster header does not receive the expected response within the estimated RTT, the transmitted packet is considered lost and the predicted data is delivered using the previous data. Also, when data packet loss occurs, the predicted data instead of real data is sent using the previous data to reduce end-to-end delay. This method, however, has the problem that it is difficult to decide on a proper RTT timeout in UWA communication [25].

As mentioned above, there are trade-offs between high propagation rate, short average end-to-end delay, and low power consumption, so it is very difficult to develop a DTN protocol satisfying all of these performance factors. Nonetheless, there is a constant need for the development of technologies that can overcome this problem and standards that support these technologies.

5.2.2.6 UWA security technology

Security technologies in UWA communication networks have mostly been proposed at the level of research focusing on UWASN.

Firstly, in the UWA physical layer, technical studies on jamming have been proposed. For doing these, the jammer, a hardware device, is deployed on the real field to study the effects of Denial-of-Service jamming attacks on the underwater acoustic networks [32]. To prevent the jamming problem in the internal threat model, a method for identifying the weaknesses and problems of the network by comparing with various models and designing security protocols for solving these problems has been proposed [33]. A method for avoiding jamming by applying reinforcement learning (e.g. jamming game scheme) to jamming prevention has also been proposed [34]. Moreover, a method to use alternative technologies such as infrared light communication [35] has been proposed to prevent jamming attacks in the underwater environments. However, since infrared rays are severely attenuated in water, it is difficult to apply them to UWA security other than short-distance security.

Concerning the security in the UWA data link layer, the CCM-UW algorithm [36] provides the security protocol in the UWA MAC. This protocol includes the CCM-UW for underwater mode, which is a modified form of the CBC-MAC mode counter for underwater acoustic communications, and a counter to include CBC-MAC, a message authentication code.

To protect against the attack to damage the reliability and integrity of the UWA communication network, the security method considering both the UWA data link layer and the UWA network layer has been proposed, too [37].

Concerning the security on the UWA network layer, a suite of security protocols for routing in the UWA communication network has also been proposed. For fixed or mobile UWA nodes, the protocol suite considers the characteristics and constraints of the sound channel in the underwater environments [38]. This protocol suite secures end-to-end confidentiality and integrity and makes it possible to safely perform node mobility and re-routing. A hole attack detection method to use directional antennas has also been proposed [39], which improves the proposed neighbour discovery protocol for wormhole attack prevention to fit for the underwater environment. This method has the advantage of reducing energy consumption because it uses the directional antenna, compared to methods that use the omnidirectional antenna in the underwater environments.

The cross-layer method [40] and framework [41] for secure UWA communication networks have also been proposed. The cross-layer method has been proposed to solve the problems of the conventional hierarchical security structure by identifying security threats in the underwater sensor networks and protecting against attacks by security issues associated with the protocol stack [40]. The Security Framework for Underwater Acoustic Sensor Networks (SecFUN) [41] is a framework for protecting against security threats from the UWA network layer to the application layer. This framework extends the Channel-Aware Routing Protocol (CARP) and it uses Galois Counter Mode and the latest technology to reduce overall energy consumption and latency time.

As described above, security in the UWA communication network has been centred on UWASN at the level of technology research. For this reason, there are few cases where UWA security technology is applied in real underwater environments.

5.2.2.7 3D UWA localization technology

UWA localization schemes using sound waves in the underwater environment are classified into the centralized localization method and the distributed localization method according to where to calculate and determine the location of UWA nodes [42]. In the centralized localization method, a central node such as the control centre or the UWA sink node (or the surface station) calculates the locations of all UWA nodes and informs location information to each UWA node. Until the central node informs the location information, each UWA node is not able to know its location. In this method, the central node informs the UWA nodes about their locations or periodically collects information for tracking the location of each UWA node. On the other hand, in the distributed localization method, each UWA node collects information necessary for position measurement from other UWA nodes and calculates its position.

Each of these methods has been studied in terms of the estimation-based scheme and the prediction-based scheme according to whether the calculated location is the current position of the UWA node or its predicted future position.

The estimation-based scheme seeks the current position of the UWA node by using the most recent information needed for position calculation. On the other hand, the prediction-based scheme is a technique that predicts the future position of a UWA node by using distant measurement, its previous positions, and anchor positions (here, an anchor means a node which knows its position). This scheme is useful especially for mobile or hybrid UWA communication networks. Motion-aware self-localization (MASL) scheme [43], hyperbola-based localization (HL) scheme [44], [45] and 3D multipower area localization scheme (3D-MALS) [46] have been proposed as an estimation-based scheme in a centralized localization scheme, whereas Collaborative Localization (CL) technique [47] has been proposed as a prediction-based scheme.

In distributed localization, estimation-based schemes have also been proposed much more than prediction-based schemes. Various schemes such as AUV-aided localization (AAL) [48], localization with directional beacons for sparse 3D underwater acoustic sensor networks (LDB) [49], using directional beacons for localization in underwater sensor networks (UDB) [50], localization with Dive'N'Rise (DNR) beacons for underwater acoustic sensor networks (DNRL) protocol [51], multi-stage localization (MSL) [52], large-scale hierarchical localization (LSHL) protocol [53], detachable elevator transceiver localization (DETL) protocol [54], anchor free localization (AFL) [55], [56], underwater positioning scheme (UPS) [57], [58], localization scheme for large scale underwater networks (LSLS) [59], etc., have been proposed as estimation-based schemes.

In the prediction-based scheme in the distributed localization scheme, only a few methods have been proposed compared to the estimation-based scheme. One of these schemes is Scalable Localization scheme with mobility prediction (SLMP) [60], which has been proposed for the mobile UWA communication network. In this method, the anchor nodes estimate the position of the future point of the UWA node using the previous positions and movement patterns of the node.

For UWA 3D localization to be realized, it is important to make the performance enhancement through the optimization of the location accuracy, long estimation or prediction time, high underwater communication overhead, high energy consumption, and large scale of measurement equipment, which are accompanied by characteristics of underwater environments. However, since most of the current techniques have been proposed only theoretically, field test verification of other performance factors including accuracy and their correction through these activities are required for practical use.

5.2.2.8 UWASN application technology

Wired networks have been used for underwater environmental monitoring and controlling where the underwater area for network application is close enough to connect the wired communication links to the terrestrial area or where installation of communication wire and electronic power lines between UWA nodes is easy. However, where it is difficult to install power lines and communication lines from the near ground, currently, WSN technology has been widely used in underwater applications. In this current WSN application, each node is located outside the water, power-supplied wirelessly by battery or through energy harvesting, and exchanges data wirelessly using radio wave communication. The underwater sensor and actuator are connected to the node by wire for power supply and data transfer. Therefore, there is a problem that the power line and the communication line between the node and the underwater sensor or the actuator should be longer than the minimum water depth to be able to use the WSN even in underwater areas for monitoring and controlling the deep underwater environment or underwater objects. Also, the radio wave communication range on the water surface tends to be very short compared with on the ground. To make matters worse, radio waves cannot be used in the underwater environment. Therefore, wired networks and WSNs have limitations on the applications to underwater areas that are far from the ground, broadly ranged or deep. For this reason, UWA communication network technology has been developed and utilized mainly in UWASN.

In the US and Europe, UWASNs are being operated in cooperation with systems such as AUV, underwater observation stations, and seafloor plants, using underwater acoustic communication as a communication means for marine exploration, marine resource mining, underwater environmental observation, coastal surveillance, etc. Especially, in the United States, various specialized projects led by the government have been performed for providing services such as marine environmental monitoring, coastal surveillance, and communication networks between unmanned submersible vehicles. Also, core and service technologies continue to expand gradually to private sectors.

SEAWEB [61], [62] and PLUSNet [63] are UWA communication application projects led by the US government for underwater environmental monitoring and port defence since the 1990s.

FRONT is also a UWASN project using SEAWEB technology and was fulfilled in 1999 to remotely control sensors widely deployed in the ocean and to provide civilian marine environmental monitoring. Also, the development of fixed UWA communication network application technology to detect and track submarines on the Western Pacific coast was conducted through the PLUSNet project in 2005.

The US Department of Defense has built a wide range of UWASNs in Canada and the US coastline since the early 2000s through the Ocean Research Interactive Observatory Networks (ORION) project [64] to defend and monitor territories. The Ocean Testbed for Underwater Wireless Networks (Ocean TUNE) project [65] has been researching building UWASN testbeds to conduct US coastal environment monitoring since 2012. Connecticut University, Washington University, UCLA, and Texas A & M University participated in this project, together.

Europe has been conducting GEOSTAR, ESONET, UAN, and Sunrise project to observe the marine environment [66].

ACMENet is a European support project for monitoring the ocean underwater environment. In this project, UWA communication was implemented between the UWA master node and UWA slave nodes with a master-slave structure. In the first experiment in the Westerschelde shipping lane in the Netherlands, UWA communication in ACMENet was used to collect channel environment data. The second experiment at the Bay of Douarnenez in France was done to identify the usefulness and limitations of the in-house designed and developed protocol. And the third experiment was planned for the monitoring and geological exploration of fish, people, and other organisms in a particular underwater area [67].

UAN [68] is also a European funded project to protect the infrastructure and equipment installed in the offshore area. In the 2011 Norwegian coastal test, the UAN, which consists of four UWA nodes, two AUVs, and a mobile node, tested performance changes on average throughput, packet loss, and RTT according to various network changes by adding or removing nodes.

GLINT10 [69] is a UWASN field test fulfilled for active anti-submarine warfare. It has an architecture that transforms the data detected by AUV, a mobile UWA node, into an active signal and beam-forms it into a radio buoy, that is, a surface station.

In 2009, through GWNU-ITRC project [70] funded by the Korean government, Ocean Sensor Network Research (OSNR) Centre at Gangneung-Wonju National University in South Korea developed technologies for a UWASN and interconnection between an RF-based terrestrial communication network and the UWASN so as to realize and operate a real-time surveillance system able to monitor underwater environment status changes of Gyungpo Lake in Korea from the terrestrial centre. In 2011 and 2013, this centre also developed the system to support controlling autonomous underwater robots and monitoring underwater environment status through the interconnection between a mobile network and a UWASN [70], [71], [72].

In 2011, Korea Research Institute of Ships and Ocean engineering (KRISO) developed the surface gateway for remote control of the UWA communication network from the terrestrial centre and succeeded in the real field test. KRISO has also completed the technology for the long-distance UWA communication up to a distance of 30 km and it is developing the technology for high-speed UWA communication within a short distance of 200 m. To control the autonomous unmanned underwater vehicle (ISIMI 200- in 2008, ISIMI 6000- in 2012) and to monitor its status information, a commercial modem is connected to that vehicle and is under operation [66].

Since 2015, Hoseo University in Korea has been in the process of developing the technology which is capable of connecting terrestrial internet networks and UWA communication networks and which is compatible with various underwater heterogeneous networks through developing UWA communication network technology based on the underwater base station.

5.3 Optical (wire/wireless) communication

5.3.1 Technical overview

5.3.1.1 Technical definition

The optical communication technology in the underwater environment can be divided into two methods: wired communication technology using fibre optic cable and wireless communication technology using LED or laser.

Wired communication technology uses the fibre-optic cable that provides robustness in the aquatic environment, as shown in Figure 5. The optical communication cable is used in the optical fibre located in the centre. Underwater optical wired communication is the same as existing optical wired communication technology in the terrestrial environment. The fibre-optic wired communication system consists of an optical transmitter, an optical multiplexer, an optical amplifier, an optical receiver, and an optical cable as shown in Figure 6 [8].

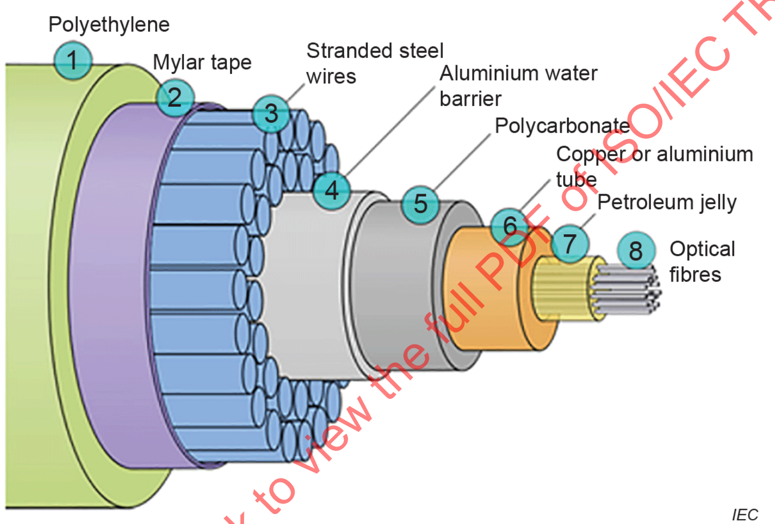


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Figure 5 – Underwater cable structure

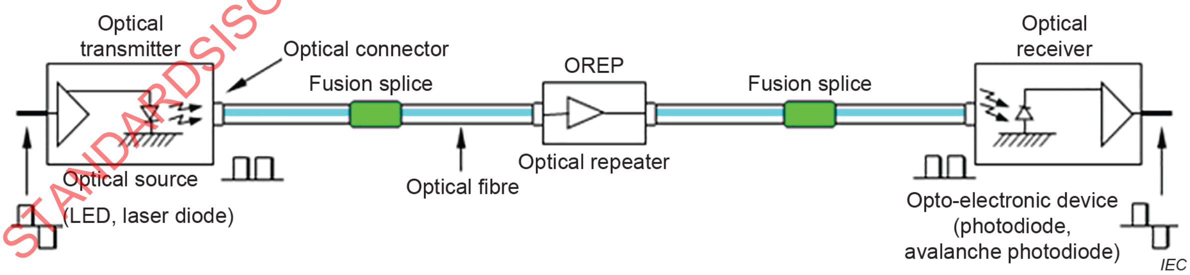

Figure 6 – Fibre-optic wired communication system overview

An optical transmitter transmits an optical signal to an optical fibre cable by converting an electrical signal into an optical signal using a light-emitting element by applying a modulation method. The optical amplifier amplifies the attenuated optical signal while passing through the optical fibre, thereby enabling long-distance communication. The optical receiver functions to convert the optical signal into an electrical signal after demodulating it according to the modulation method.

In the underwater optical wireless communication technology, a signal is transmitted without a transmission path; it is composed of an optical fibre linking a transmitting unit and a receiving unit. Since the data is transferred to the water medium, the cost and installation time required for the optical fibre installation are significantly reduced compared with wired optical communication, thereby forming an effective communication network. Also, since wireless optical communication has become possible due to the development of optical elements, it has the advantage of being able to communicate at a potential capacity of hundreds of gigabits per second (Gbit/s) and ultra-high-speed communication and to be free from frequency usage, unlike existing RF wireless communication. However, due to the severe attenuation effect of optical signals in water, the communication distance is limited to a few hundred metres, and it has a disadvantage that it is greatly influenced by the underwater environment such as turbidity.

5.3.1.2 Channel characteristics

In the optical wired communication system, the optical fibre of the underwater cable becomes the channel. Optical fibre is a very high-purity glass fibre. When light is passed through an optical fibre, the light does not come out of the fibre but passes through it. As the fibre is bent, the light proceeds accordingly. This is the use of total reflection of light in glass fibres. Total reflection refers to the phenomenon that light is reflected at the interface when light travels from a substance with a high refractive index (glass) to a substance with a low refractive index (air). Also, to reduce the attenuation of the light, it is better to remove the impurities in the glass to make it completely transparent. The glass purity used for optical fibre is 99,999 999 9 % or more. This is almost the same as the purity of a silicon single crystal used in a transistor or an LSI. This optical fibre transmission loss (light attenuation) is less than 0,2 dB per kilometre, which is an unimaginable value for copper lines [73]. The characteristics of the optical fibre cable are summarized as follows.

- Copper cables have a practical limit of several megabits per second for pair lines and hundreds of megabits per second for coaxial cables, but optical fibres can transmit very wide frequency band signals over gigabits per second.
- Even if it is combined with reinforcement cloth, one strand of optical fibre is 0,4 mm in diameter and it is only about one-thirtieth of the thickness of the coaxial cable.
- Optical fibre has the advantage of less attenuation of light so that fewer repeaters can be installed even in long-distance transmission.
- In the air, there are noises from thunderstorms, trains, automobiles, and factories. Since the optical fibre does not go through electricity, it does not get disturbed by the noise.
- Fibre-optic communication has a low crosstalk phenomenon, so it has high-security calls.

In the optical wireless communication system, water becomes a communication channel. When the optical signal is transmitted in water, it travels about 150 333,3 times faster than that of the sound wave. The propagation distance of the optical signal differs according to the frequency range. The frequency range of the optical signal used in the water mainly uses a blue-green laser or LED that has the lowest signal attenuation [74], [75], [76]. The main optical properties of water are the spectral absorption coefficient and the spectral volume scattering function. Absorption of optical signals in water is a process of converting electromagnetic radiation into heat, that is, a process of absorbing energy to be re-emitted. Absorption occurs in the chlorophyll of phytoplankton, in the colour of organic matter, in water molecules, and saline dissolved in water. The direction of the optical signal changes due to scattering. Scattering is caused by salt ions and particulate matter in pure water. The attenuation coefficient of the optical signal is expressed as total energy lost due to absorption and scattering. In clear water, the signal attenuation is about 0,39 dB per metre, and in muddy water, the signal attenuation is about 11 dB per metre [77]. In addition to absorption and scattering, there are noise components in the water that affect optical signal transmission. Types of noise include wave noise, quantum noise, optical over-noise, optical background noise, and optical receiver current noise. Wave noise or background noise occurs in the underwater environment, optical over-noise is caused by the incompleteness of the transmitter, and quantum noise is caused by the change of the photon number of the optical receiver. The optical receiver's current noise is caused by current leakage, and such noise occurs in electronic circuits.

5.3.1.3 Background

Wired optical communication technology has a long history. In 1966, C. Kao and others demonstrated the possibility of optical communication with the track. In 1970, Corning, USA, developed an optical fibre with 20 dB per kilometre of attenuation of light so that wired optical communication technology became practical. Since then, low-loss optical fibre has been developed and applied to a 10 Gbit/s optical transmission system [78]. With the increase in demand for international telecommunications, underwater optical cable systems have grown rapidly since the 1990s. After the first optical communication system was developed by Trans-Pacific Cable 3 (TPC-3) in 1989, optical amplification technology was introduced in TPC-5 in 1996, and WDM transmission technology was introduced in China-US cable, which was launched in 1999 [78]. The introduction of WDM transmission technology spurred the expansion of transmission capacity, which increased 1 000 times in five years after 1999. After that, the construction of new systems was suspended for several years from the early 2000s, but construction has resumed with the recent increase in demand. Underwater optical wired communication systems differ from terrestrial optical communication systems in many respects. First, in the trans-Pacific cable system, since the maximum depth of the sea reaches 8 000 m, high voltage and high tension that can withstand the water depth are required for the cable and the repeater. Also, high reliability is required since the optical cables mounted on the seabed are difficult to repair and maintain. Moreover, due to the limitation of the size of the repeater and the power consumption, it is very important to increase the transmission capacity per core wire because the number of core wires is limited. In the optical amplification repeater system, since transmission deterioration factors such as noise and wavelength dispersion accumulate over a long distance of several thousand kilometres, a transmission technique for reducing the influence is essential. Currently, as shown in Figure 7, a huge length of underwater cable is buried to transmit data at a transmission rate of 100 Gbit/s or more [79].

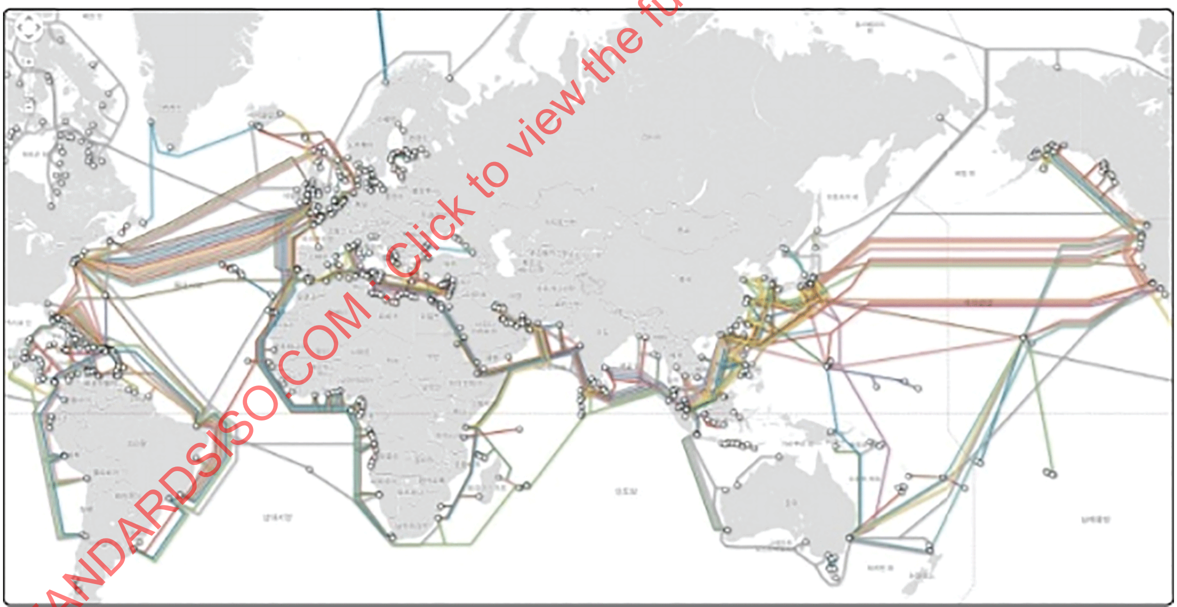

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Figure 7 – Current underwater cable map

Regarding optical wireless communication technology in water, Duntley announced that light of 450 nm to 550 nm wavelength corresponding to a blue-green spectrum in the water had a relatively low attenuation characteristic in 1963, and this was confirmed experimentally by Gilbert et al. [80], [81]. Based on this technology, underwater optical wireless communication technology emerged. At first, underwater optical wireless communication was mainly used for military purposes, especially submarine communications. In 1976, Karp demonstrated the feasibility of optical wireless communication between underwater and terrestrial (satellite) terminals [82]. In 1977, researchers at the Lawrence Livermore Institute at the University of California proposed a one-way optical communication system from the coast to a submarine [83]. In 1992, it was shown that the optical signals with a wavelength of 514 nm showed a transmission rate of 50 Mbit/s in proximity using an arc-ion laser [84]. In 1995, LED-based underwater optical wireless communication was theoretically verified to be able to communicate at a transmission rate of 10 Mbit/s at a distance of 20 m [85].

In early 2000, BlueComm [2] introduced a product capable of 20 Mbit/s underwater data transmission at a distance of 200 m. Several products have also been commercialized, including Ambalux's [3] underwater optical wireless communication system, which can provide the same data transmission rate over short distances of 20 m. In 2010, a bidirectional communication link was developed that uses high power LED arrays and a separate pulse spacing modulation to achieve high data rates and high power consumption rates.

5.3.2 Trend of technology (modern communication trends)

5.3.2.1 Underwater optical wired communication system

Recently, in the trans-Pacific optical fibre communication system, a system with a transmission capacity of 1 Tbit/s was realized by multiplexing and transmitting wavelengths at a wavelength of about 0,3 nm with a signal of a transmission rate of 10 Gbit/s at 100 channels. In the modulation scheme, the intensity modulation signal that transmits information by flickering has been used. However, a phase modulation signal that has higher reception sensitivity than that of the intensity modulation signal has been introduced recently. Also, high-performance error correction codes are being introduced to expand system margins. As the transmission line, a low-noise optical amplifier whose gain band is extended to about 30 nm and a dispersion management transmission line are used. In the dispersion management transmission line, to avoid the influence of the wavelength dependence of the optical fibre wavelength dispersion that is accumulated during transmission, the use of two types of optical fibres whose dispersion characteristics are opposite realizes a flat wavelength dispersion characteristic over a wide band.

Underwater optical cable communication system consists of an optical transmitter, an optical multiplexer, an optical amplifier, an optical receiver, and an optical cable as shown in Figure 8 [8]. Transmitter diodes of optical transmitters currently use LEDs at low speeds and laser diodes at high speeds. A photodiode is used as a light-receiving element of the optical receiver. A photodiode is used as a light-receiving element of the optical receiver. The performance of the light source used in optical wired communication has optical power (output), line width life, oscillation wavelength, and temperature dependency. Laser diodes include distributed feedback (DFB) type and feedback (FB) type. Avalanche photodiode (APD), PIN photodiode, etc. are used as the light-receiving element, and APD has excellent sensitivity.

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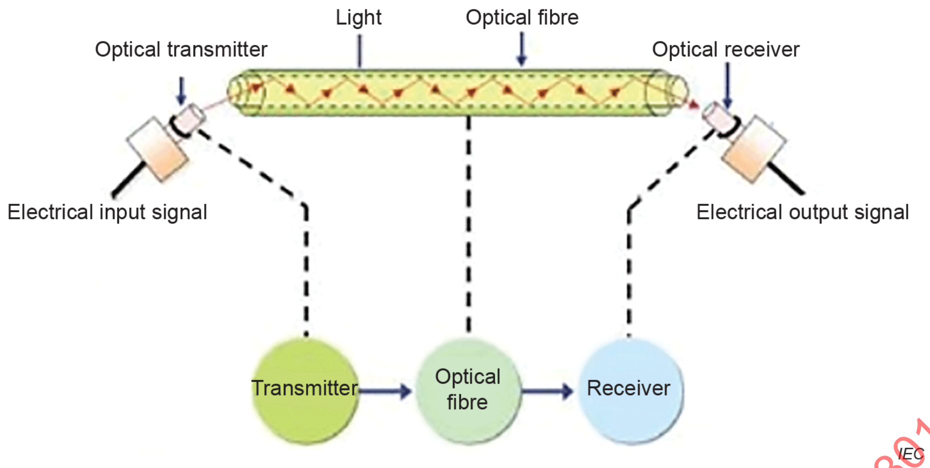


Figure 8 – Optical wired communication system overview

The optical fibre has a single-mode optical fibre, mainly used for long-distance, and a multi-mode optical fibre available at a short distance. In water, single-mode optical fibre is used for most long-distance communication. Currently, the transmission method mainly uses WDM technology. WDM technology is an optical communication technology that uses a plurality of wavelengths in one optical fibre to increase the data transmission rate and allow a plurality of users to make communication equitable. There are several types of WDM technology, such as coarse WDM (CWDM), dense WDM (DWDM), and ultra-dense WDM (UDWDM) as shown in Figure 9 [86]. Optical amplifiers are essential for intercontinental long-distance communication in water and each exists between 40 km and 120 km. Prior to the development of optical amplification technology, there was a relay in which optical signal was converted into an electrical signal during transmission, and the signal was re-formed, re-timed, re-generated, and then relayed to the optical signal. However, with the development of the optical amplification technology, the optical signal can be amplified from the optical signal without optical/photoelectric conversion so that long-distance transmission becomes possible. The optical amplifier is classified as a post-amplifier, a line amplifier, or a pre-amplifier depending on its position in a communication system. Also, in accordance with amplification principles, an optical amplifier is classified as a semiconductor optical amplifier (SOA) or an optical fibre amplifier. Semiconductor optical amplifiers are compact but have a small gain. Although the optical fibre amplifier is large, high amplification can be obtained by increasing its output, which is suitable for high-speed and large-capacity communication. Optical fibre amplifiers can be classified into erbium-doped fibre amplifier (EDFA), erbium-doped waveguide amplifier (EDWA), praseodymium-doped fluoride fibre amplifier (PDFFA) and RAMAN amplifier [86].

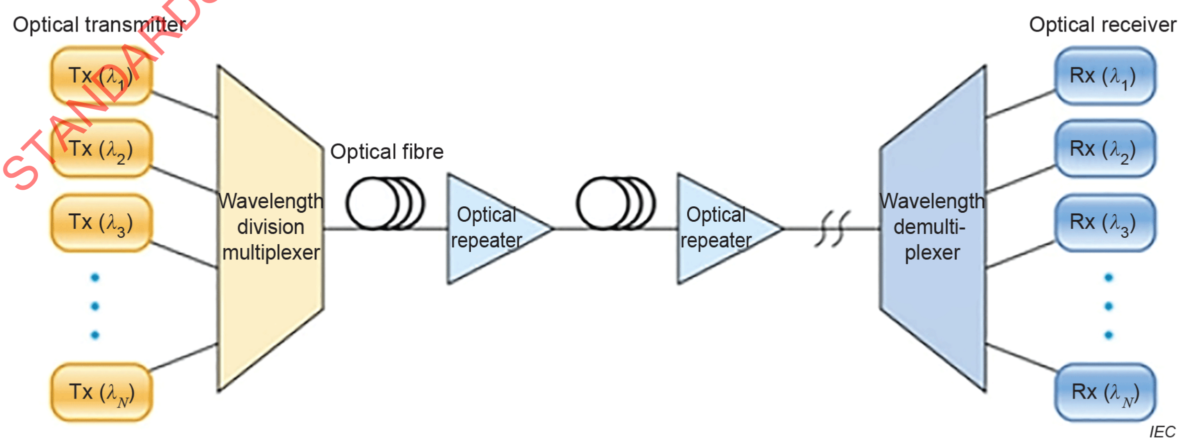


Figure 9 – Optical wired communication system based on WDM technology

In the optical wire communication system, the modulation technique changes the amplitude of an optical signal to generate a signal by changing the magnitude of the driving current flowing through the light emitting element or by superimposing the signal current at a constant driving bias current, and then changes the magnitude of the current flowing through the light emitting element. When a modulation signal is analogue, it is called an analogue transmission system; when a modulation signal is digital, it is called a digital transmission system. In the digital transmission system, information to be transmitted is converted into two signals of '1' or '0'. Alternatively, instead of changing the magnitude of the current flowing through the light emitting element, a method of changing the phase, frequency, or intensity of light in accordance with information to be transmitted when light passes through an optical circuit which carries information from outside of the light-emitting element is referred to as an external modulation method. This method is often used as a modulation method in coherence communication. In coherent communication, ASK, FSK, and PSK are signals that put signals on the light wave.

The disadvantage of underwater optical cable communication technology is that it is very expensive to lay optical cables on the sea floor. To conduct optical communication using an underwater optical cable, the optical cable should be embedded in the sea floor, and the optical cable should use a cable having a total diameter of up to 60 mm to prevent damage to the underwater environment. In general, the cable usually consists of a bundle of dedicated lines and optical fibre for Internet/telephone lines, polyethylene wrapped around it, and metal wires to add durability and firmness. In the case of optical cables buried at the bottom of the sea, the reason for covering a wire with metal wire clothes is to avoid any damage from fishery activities. If an optical cable breaks due to an accident, a repair ship first searches for the location where it was disconnected. It will find one of the broken ends and then fix the damaged area, moor it to a buoy, and put it back into the sea. Then it will pull the other damaged end out of the sea, fix the damage, and find the buoy while carrying the fixed wire on the boat. Then, it will pull up one side of the repaired cable hanging at the buoys, connect both ends of the cable, and put it back into the sea, and the restoration work is over.

To install the fibre optic cable at the bottom of the sea, the fibre optic cable is loaded on the cable-ship and mounted while moving slowly from the target starting point. The method of burying the cable is to put the undersea optical cable at the bottom after digging 2 m to 3 m into the sea bed with the plough burying machine.

5.3.2.2 Underwater optical wireless communication system

Underwater optical wireless communication technology is an underwater communication method to support high data transmission rates without using underwater optical cables, which are expensive to install, maintain, and repair.

Underwater optical communication technology can transmit data at a rate of megabits to gigabits per second at a distance of several tens of metres to several hundred metres due to the high frequency of the optical carrier. The optical signal in the underwater environments has various extreme difficulties due to water absorption or scattering due to aquatic particles or strong disturbance caused by the sun. However, since it is the only technology capable of high-speed transmission over wireless at a distance of several tens of metres to several hundred metres, many studies have been made. The main problems of underwater optical wireless communication technology are as follows.

- The blue and green spectrums have the lowest transmission attenuation coefficients in the optical signal, but the absorption and scattering are very seriously large due to water molecules and other particulate matter, resulting in severe multipath fading. Due to the effect of absorption and scattering, communication over several hundred metres is difficult.
- Underwater optical link due to misalignment between the optical transmitter and receiver can be unstable. Misalignment of the optical transceiver due to buoy movement from waves of the sea surface can cause a serious problem in communication.
- Underwater optical wireless communication system is greatly influenced in performance and life span by seawater flow, pressure, temperature, and salinity. Also, the efficiency of power consumption is essential because the battery should be powered.

As a light source for underwater wireless communication, LED or laser is mainly used, and the spectrum mainly uses a cyan part. Blue-green LEDs are generally preferred in shallow water. For systems operating in deep clear waters, laser-based systems are preferred. The output of a blue-green spectrum laser or LED is in the range of 10 mW to 10 W. LEDs and lasers, which are mainly used for underwater wireless communication, have advantages and disadvantages.

LED-based systems are less sensitive to the effects of underwater channels compared to lasers due to their wide viewing angles. The performance of an LED-based system is determined by beam divergence and geometric effects due to the dynamic range and field of view of the receiver. LEDs are inexpensive and easy to develop, but the range of the link is very limited due to the incoherent light beam and the rich range of the omnidirectional light. Link ranges can be increased by using high power LEDs or by converting to non-directional coverage with unidirectional links using a focused optic or LED array. LEDs, such as those made of gallium indium nitride (InGaN) on silicon carbide (SiC) substrates, are configured in an array to increase the light output to provide an output of 10 mW. A multi-wavelength technique combined with a rate-adaptive technique can be used to improve system performance [87].

Laser-based systems have advantages over longer distances, higher data rates, and lower latency than using LEDs as light sources. The coherent laser beam provides a good quality output, but the intensity of the signal is rapidly reduced by underwater scattering and turbulence. Optical wireless communication is possible with a laser about 100 m in clear water and 30 m to 50 m in muddy (cloudy) conditions. Also, lasers can support high data rates due to the large modulation bandwidth (> 1 GHz) when compared to LEDs with modulating bandwidths of less than 200 MHz [87].

Modulation technology for underwater optical communication has mostly used IM technology, which is mainly used for FSO communication on terrestrial. OOK modulation is the most widely used and the simplest IM method in FSO communication systems. OOK modulation is a binary level modulation scheme, in which a light pulse that occupies some or all of the bit duration represents a single data bit '1'. On the other hand, the absence of optical pulses represents a single data bit '0'. The OOK modulation method has two pulse formats: RZ and NRZ. In RZ format, a pulse with a duration that occupies only a fraction of the bit length is defined as representing a '1'. However, the pulse duration occupies the entire bit duration in the NRZ scheme. RZ-OOK is more energy-efficient than NRZ-OOK but consumes more channel bandwidth. Due to the severe absorption and scattering in the aquatic environment, the transmitted OOK signal is affected by channel fading. To reduce this effect and achieve optimal OOK signal detection, most underwater optical wireless communication OOK receivers adapt to dynamic threshold techniques. The dynamic threshold technique is determined based on an estimate of channel fading. The underwater optical wireless communication OOK system can use various channel estimation methods of the FSO communication system such as a pilot symbol method, maximum likelihood (ML) method, and ML sequence method.

Two disadvantages of OOK for underwater optical wireless communications are low energy efficiency and spectral efficiency. However, considering simplicity, OOK modulation is still the most commonly used IM system for underwater optical wireless communication systems [88], [89], [90].

Pulse position modulation (PPM) is a modulation technique widely used in underwater optical wireless communication systems. Compared to OOK modulation, PPM has high energy efficiency and does not require dynamic threshold techniques. However, the bandwidth efficiency is low and the complexity of the transceiver is relatively high. However, recent studies have been carried out from 4-PPM to 8-PPM and 16-PPM, and studies for increasing the bandwidth efficiency have been actively conducted. The main disadvantage of PPM modulation is that timing synchronization needs to be accurate. Timing error leads to serious performance degradation of the system. Recently, research has been conducted from 4-PPM to 8-PPM and 16-PPM [91], [92], [93].

Pulse width modulation (PWM), a modulation scheme similar to PPM, is also used in underwater optical wireless communication systems. It is a method of representing a data symbol using a relative position of a pulse. The PWM scheme has high spectral efficiency and little influence by ISI. Also, Digital pulse interval modulation (DPIM) is actively used in underwater optical wireless communication systems. DPIM is transmitted with an "On" optical pulse slot, followed by an "Off" slot. The number of "Off" slots depends on the decimal value of the transmitted symbols, and additional guard slots are generally added to avoid sending continuous "On" pulses. Compared to PPM and PWM, which require slot and symbol level synchronization, digital pulse interval modulation is an asynchronous modulation scheme with variable symbol length. Also, for variable symbol length, DPIM has a higher spectral efficiency than PPM and PWM. The most important problem of DPIM is error diffusion in demodulation. If the "Off" slot is demodulated to "On", all subsequent symbols might be incorrect [94], [95].

Coherent modulation is also applied to underwater optical wireless communication systems. The coherent modulation scheme encodes information about the amplitude, polarization, or the phase of the optical carrier. Compared to the IM scheme, coherent modulation has high receiver sensitivity, higher system spectral efficiency, and stronger characteristics of background noise, but higher implementation complexity. The common coherent modulation used in UWOC systems includes quadrature amplitude modulation (QAM), PSK, and polarization shift keying (PolSK). Experimental studies on BPSK, quadrature PSK (QPSK), 16-QAM, and 32-QAM have also been conducted and it has been demonstrated that PSK modulation outperforms other modulation schemes in terms of data rate and BER. However, poor power efficiency is a problem. In BPolSK, the signal is modulated by changing the polarization of the light. Because the polarization state of light is less sensitive than the amplitude, phase, or intensity of the optical signal, BPolSK is robust to other channel interference, such as underwater turbulence and ambient light. PolSK is ideal for optical wireless communications, but it provides short transmission distances and low data transmission rates. This modulation scheme has been studied to combine the existing PPM and PolSK by transmitting a series of PPM symbols in various polarization directions [96], [97], [98], [99].

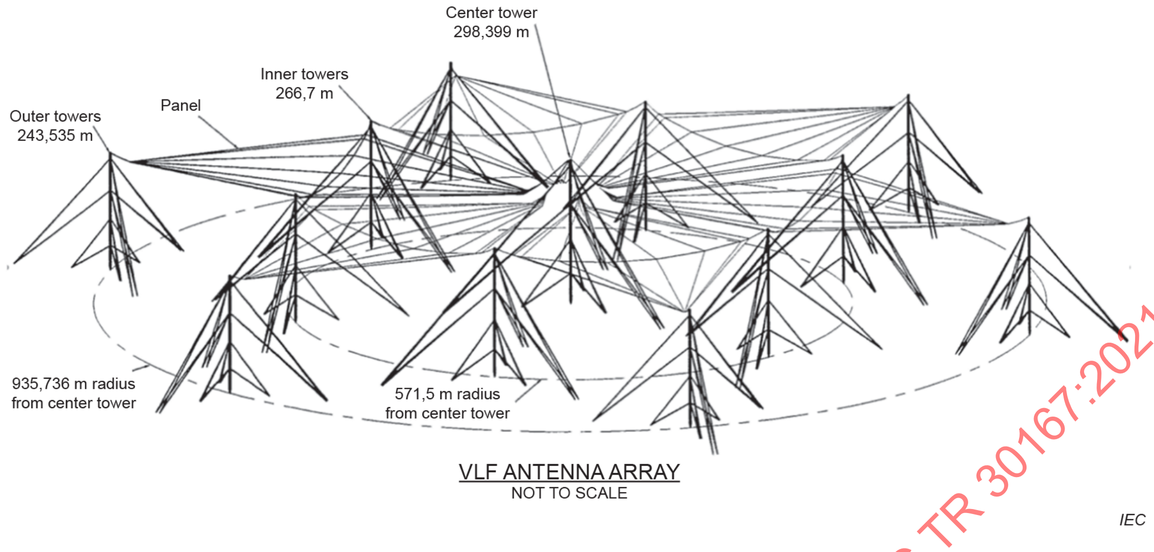
5.4 Very Low Frequency (VLF)/Extremely Low Frequency (ELF)

5.4.1 Technical overview

5.4.1.1 Technical definition

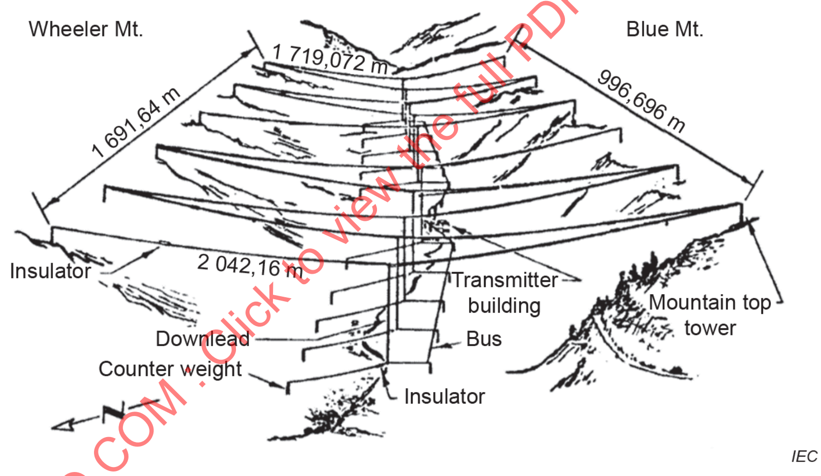
ELF communication in water has the characteristic that electromagnetic waves in ELF bands can communicate over long distances and can pass through the seawater to depths of up to several hundred metres. If ELF signals are transmitted from terrestrial ELF transmission stations using these characteristics, a submarine can receive these signals while maintaining the operating depth without reducing the speed of the submarine or rising to the surface. The ELF band used for submarine communication in the water uses the SLF (30 Hz to 300 Hz) band, and the VLF (3 kHz to 30 kHz) band defined by the International Telecommunication Union (ITU). In ELF communication, the size of the antenna is the biggest constraint to implement due to the VLF. The ELF transmission station in Michigan, USA has 52 km of antenna, the Russian ELF transmission station ZEVS has 60 km of antenna, and the VLF transmission station has several square kilometres of antenna. For ELF transmission, a dedicated power plant is required, although the emitted power by radiation is only a few watts, and ELF transmission messages can be received almost anywhere. (There is a record in the station in Antarctica (latitude 78° south, longitude 167° west) that detected transmission when the Russian Navy operated the ZEVS antenna.) Due to the technical difficulty of constructing ELF transmitters, the United States, Russia and India are the only countries known to have built ELF communications facilities.

On the other hand, a VLF wave of 3 kHz to 30 kHz can pass through a depth of about 10 m to 40 m, and a submarine at low water depth can use this frequency. For VLF communication, a 180-m-high tower as shown in Figure 10 or an extended mountain-valley as shown in Figure 11 is generally used, and the aircraft antenna is generally 7 km long (To achieve more than 50 % efficiency, the tower height of the VLF antenna is 150 m to 300 m, with an area of 1 km^2).



SOURCE: https://en.wikipedia.org/wiki/VLF_Transmitter_Cutler#/media/File:Cutler_VLF_antenna_array.png [viewed 2021-03-16]. Reproduced with permission.

Figure 10 – Trideco antenna tower array used in the US Navy's Cutler station



SOURCE: https://en.wikipedia.org/wiki/Jim_Creek_Naval_Radio_Station#/media/File:Jim_Creek_VLF_antenna.png [viewed 2021-03-16]. Reproduced with permission.

Figure 11 – Valley-span antenna type used by the US navy station, Jim Creek

5.4.1.2 Channel characteristics

Electromagnetic waves in ELF bands have extremely long wavelengths and can be diffracted around large objects, so they can travel along the Earth's surface without being blocked by mountains or the horizon. Electromagnetic waves in the ELF band can propagate long distances according to the Earth's ionospheric waveguide mechanism. The Earth is surrounded by a layer of charged particles (ions) called the D layer, which can reflect ELF waves in the atmosphere at an altitude of about 60 km, which is the bottom of the ionosphere (60 km to 1 000 km above the atmosphere). The space between the conductive Earth's surface and the conductive D layer serves as a parallel plate waveguide that holds the ELF waves so that they can transmit long distances without escaping into the atmosphere. The ELF wave has a very low attenuation of 1 dB to 2 dB per 1 000 km, providing the possibility of global communication with one transmitter. VLF waves have a characteristic of being able to be delivered from 5 000 km to 20 000 km with a small attenuation of 2 dB to 3 dB and a slight fading at high frequencies and being very stable.

VLF waves are reflected in a transverse magnetic (TM) mode alternating between the Earth's surface and the ionosphere while moving in a zigzag form around the Earth. Since the ELF wave is less than one wavelength compared to the VLF wave, the only mode that can pass at the ELF frequency is the transverse electromagnetic (TEM) mode in vertical polarization with the vertical electric field and horizontal magnetic field.

5.4.1.3 Background

In 1958, researchers and scientists theorized that VLF radio waves can penetrate deep into the oceans and communicate with deeply submerged nuclear power submarines. The US Navy was concerned about the possibility of establishing a communication system to send messages to underwater submarines such as Polaris missile boats. (Research related to this was kept secret for 10 years.)

The US Navy has studied several different concepts of ELF transmission. The project Sanguine envisioned a surface hardened, dispersed, and deployed ELF radio communication system; SHELF proposed a deep underground ELF communication system; and SEAFARE (or Surface ELF Antenna for addressing receivers that are used remotely) proposed an unhardened surface-deployed ELF antenna system using buried antennas. Finally, the ELF system we know today (ELF Clam Lake Sheet Communication System Fence Relief Program with two transmitter site locations, transmitter facility, and ground antenna system at Clam Lake transmitter site) was finally selected for implementation.

Early theoretical and experimental research began at the RCA David Sarnoff Institute in Princeton, NJ, between 1958 and 1963. The test site, known as the Alpha Test Site, was built in 1962 with facilities in North Carolina and Virginia and was used to prove the concept by sending signals to a deeply submerged submarine 4 000 km away the following year. In 1968, the US Navy built a test facility at the Chequamegon National Forest in northern Wisconsin.

Both above-ground and buried antenna system tests, as well as initial scientific studies of potential biological and ecological effects of ELF transmissions, were conducted at the Wisconsin Test Facility. The US Navy has successfully carried out research to avoid significant biological and ecological impacts and procedures to reduce the impact of ELF transmissions on utilities and other long metal objects (the Interference Mitigation Program). All naval tests on these systems were conducted in the 40 Hz to 50 Hz and 70 Hz to 80 Hz bands. (Code named project Seafarer, a US Navy system proposed by Sanguine operates at 76 Hz.)

During the mid to late 1970s, Wisconsin laboratory facilities were used to send messages to submarines under the ice caps of the Atlantic, Pacific, and Arctic oceans to assess the usefulness of the system. Then, the Wisconsin test facility was upgraded and redesigned as a Wisconsin transmitter facility in the mid-1980s, and Republic, Michigan, about 240 km away, was proposed as a second transmission facility. In 1985, the Clam Lake site gained initial operational capability. When the Michigan site was fully operational in the autumn of 1989, Wisconsin was renamed to Naval Radio Transmitter Facility Clam Lake.

The United States retained two stations in the Chequamegon-Nicolet National Forest in Wisconsin and the Escanaba River State Forest in Michigan until the end of September 2004 (originally named Sanguine project, then shrunk and renamed ELF project prior to construction). Both stations used a long power line (22,5 km to 45 km) called the ground dipole, and a significant amount of power was consumed to operate the system.

Early on, transmissions for the VLF communication used a spark-gap transmitter with a modified configuration used by Heinrich Hertz to detect electromagnetic waves. Guglielmo Marconi of Italy was the first to know that Hertz's electromagnetic waves could be used for signalling, and repeated attempts and mistakes to develop ideas and received a patent for the first wireless communication device in June 1896. Marconi founded the Marconi Company for commercial use of his invention, and the international radio station first transmitted a message between England and France in 1899. In 1901, Marconi equipment sent its first trans-Atlantic signal using the sky-high fixed antenna fixed by kite and balloon in Canada's Newfoundland from the Poldhu area of Cornwall, England. The first radio transmission frequency across the Atlantic was not known because a cymometer which can measure the frequency was not invented until 1904. In 1901, the first interference occurred between stations in New York Harbor. The Marconi Company, the US wireless telephone, telegraph company, and the De Forest Company all wanted to report international yacht races at the same time. Perhaps it was the first case of radio interference and the first radio interruption (jamming) fight in the United States.

The initial impetus for long-range wireless communications stems from the demands of diverse colonial empires for cross-ocean communication services and the need for command and control of various naval forces. Over the years, wireless communication meant low frequencies. The first commercial Atlantic services (between Glace Bay and Newfoundland in Canada, and Clifden in Ireland, started in 1907) used a low-frequency band of 82 kHz. Between 1910 and 1912, commercial operation was promoted using 12 kHz to 13 kHz frequency for long-distance communication.

Between World War I and World War II, VLF transmission was not used for commercial purposes by improving high-frequency technology to create commercially feasible HF communications. However, VLF networks have continued to be used by people with the need for high-reliability, long-distance communications that can balance against greater costs.

In 1941, Goliath station in Kalbe, Germany, began to transmit 1 000 kW at 16,5 kHz, with 18 masts with a height of 175 m to 200 m (top cover range of 1,26 km^2). Despite having a galvanized steel grounding system instead of copper, the final antenna had nearly 50 % efficiency at the lowest operating frequency (twice as efficient as before). Russia built larger VLF transmitters and antennas to provide military messaging around the world, both during and after World War II. When the US Navy radio transmission facility in Cutler, Maine was established in 1961, the signal could be heard from anywhere in the world.

VLF transmission for aviation began in the early 1960s, and the aircraft flying at 5 km altitude was equipped with more than 7 km of antennas. Longer antennas provide better efficiency for surface communication than shorter ones and are more effective in the vertical direction. To optimize the vertical direction, the antenna is made in the shape of a corkscrew mechanism behind and below the plane. Although a new VLF transmission station has been constructed, most of the original transmission stations are still in operation due to the large investment needed to make them. For example, the VLF Transmission Station in Annapolis, Maryland, was built in 1918 and changed in 1922 and 1941, and this transmission station and VLF communication systems are adapting to the improved technologies and communication systems.

5.4.2 Trend of technology (modern communication trends)

5.4.2.1 ELF communication technology in the US

The US Navy's ELF communication system is the only military operational communication system that can penetrate deeper into the sea and is indeed jam-proof from nature and artificial interference. The ELF system allows the submarine to receive communications without slowing down or operating on the surface. Thus, the ELF system was used as an important military instrument against aircraft and satellite systems to detect submarines using non-acoustic phenomena such as Kelvin wakes and internal waves near the surface.

In 1968, the US Navy released plans called Sanguine for an ELF system in Wisconsin that could survive a nuclear attack. The Sanguine concept envisions more than 100 buried unmanned transmitter bunkers (capsules, about 6 m (diameter) × 1,8 m (length)) and can be operated at 72 Hz to 80 Hz. Each transmitter was designed to operate with its emergency power system and an antenna cable with a diameter of about 5 cm and a length of about 64 km to 80 km was buried at a depth of about 1,2 m to 1,8 m. A total of 9 656 km of cable will fall from 4,8 km to 8 km in a grid arrangement and will require an area of 16 835 km^2.

Due to official concerns about the physical and environmental impacts of electromagnetic radiation, the US Navy abandoned the Wisconsin scheme and opted for Texas as another Sanguine base, but it was withdrawn because of public resistance. After two unsuccessful attempts, the US Navy rebuilt the ELF project and in 1975 renamed it Seafarer to cover Sanguine's stigma. Nuclear viability requirements were abandoned and transmitters were installed on the ground, but the cables remained buried. Environmental impact studies for three candidate sites (Nellis Air Force Base and Nuclear Test Facility in Nevada, White Sands Missiles in New Mexico, Peninsula in the north of Michigan) began in 1975, and Michigan was selected in 1977 to complete an environmental impact statement (EIS).

Another alternative concept of Seafarer was called Pacific Intertie Strategic Communications ELF System (PISCS) and included the deployment of 1 370 km of power lines from the Dalles Dam in Oregon to Los Angeles. To improve the ability of long parallel antennas to transmit signals in only one direction, a two-dimensional grid (scalable modular format) has been proposed for Seafarer that is able to transmit in all directions.

Also, the US Navy considered embedding super hard ELF system (SHELF) within a 1,6 km vertical shaft tunnel for extreme survival and has also installed a SHELF transmitter and a power unit that is capable of supplying power by itself. Tens of millions of dollars were invested in SHELF and research until 1978. Concerning the Seafarer, after Michigan was selected, the number of transmitters was kept at three, cable in an antenna network was doubled to 3 862 km, grid area decreased from between 6,4 km and 9,7 km to 5,6 km and the entire grid occupied 12 173 km^2. In May 1977, it was scheduled to begin full-scale development of Seafarer, but in March 1977 the Governor of Michigan exercised his veto power on the project, and President Carter ordered further research, deciding to suspend Seafarer in February 1978 and to implement ELF.

The reduced-scale ELF system was used briefly and in December 1977 the US Navy recommended the construction of a modified concept called "Austere ELF" in Michigan's Upper Peninsula. This project was officially announced in March 1978. The project consists of 209 km of antenna cables divided into three of 51,5 km, 72,4 km, and 85,3 km and this antenna ended at K.I. Sawyer Air Force Base where one transmitter was installed.

Cables are buried along public roads and other public corridors. The Wisconsin test facility, which is about 265 km away, was upgraded to a transmitter in Michigan through a leased telephone line. Together, the two facilities provide five antenna cables, a total of 254 km of cable, and the cables in the Wisconsin facility are on the ground.

Austere ELF was supposed to run in October 1983, but in early 1981, Austere ELF suffered from the inhabitants' opposition and budget constraints. Secretary of the Navy John F. Lehman urged Defense Secretary Caspar Weinberger to dismiss the ELF communications system, but the Reagan administration did not agree with the US Department of Defense opinion and assessment. In October 1981 the Pentagon, under direction from the President, released plans for a further scaled down ELF system called Project ELF.

It was a three-pronged effort to (1) upgrade the Wisconsin facility, (2) install a second transmitter with the antenna at K.I. Sawyer Air Force Base in Michigan, and (3) install ELF receivers in submarines. Plans for Michigan were similar to Austere ELF except that 90 km of cable in Escanaba State Forest was planned, exactly double of that at the existing Wisconsin test facility and installed above ground. Original plans were for initial operation in 1985 and full operation with receivers on all submarines by 1987. It was not until the 1990s that all submarines had ELF receivers.

In addition to the permanent Project ELF site in Wisconsin and Michigan, the Pentagon has also shown interest in a rapidly-deployable ELF system. One such concept is a mobile system using truck and trailers, variously referred to as "Mobile ELF", "Elusive Voice" and "Transportable ELF". As early as 1982, five million dollars had been appropriated to investigate this concept. Mobile ELF could eventually consist of a fleet of trucks and trailers carrying 48 km of ELF cables, transmitters, generators, security equipment, and radiation protection equipment.

Deployment would probably take place in Wisconsin and Michigan. Presumably, during time of emergency, these trucks would roll out on the highways and reel out the cable in segments. The segments would then be connected to form a 48 km antenna element. With the mobile transmitter slaved to Project ELF transmitters, this would provide rapid expansion of that system to provide higher transmission speeds.

Another form of ELF that can be deployed quickly is the "balloon ELF". In early 1978, it was suggested to use balloons to lift vertical array antennas, and in 1981 the contract was signed with Pacific Sierra Research Corporation in Santa Monica to study the feasibility of balloon ELF. A report by the Defense Advanced Research Projects Agency (DARPA) in 1985 described the VLF/ELF transportable communication system and demonstrated it with the Navy as a vertical dipole antenna supported by a balloon. Balloon ELF is another complementary method to increase the Project ELF data rate in imminent crises.

ELF is a robust system of 9 656 km of underground cables covering hundreds of buried transmitters and 16 835 km^2. When this system was not accepted, the Navy proposed a Seafarer with three terrestrial transmitters and 3 862 km of underground cable, which occupies 12 173 km^2. Then it was scaled down to Austere ELF with two surface transmitters and 254 km of cable.

The current Project ELF still has two transmitters and only 135 km of cable hung on telephone poles. In June 1977 the ad hoc ELF review group of the Secretary of Defense decided that a small ELF system would be of marginal utility and was not credible as the ultimate ELF system. However, it recommended building the small ELF because the modified version would provide a basis for future system growth if ELF requirements later increased.

The ELF system is modular and can be expanded quickly with mobile systems during emergencies to increase the data rate. Both truck mobile and balloon suspension have been investigated.

The Navy's ELF system operates at about 76 Hz, and ELF radio can pass through about 30 m (100 ft) of deep water while communicating with the submarines and maintaining stealth capability. On October 1, 1989, the entire ELF communication system was fully operational and two transmission sites began synchronized transmission of ELF broadcasts to the submarine fleet 24 hours a day, 7 days a week. US facilities were used between 1985 and 2004 and are now dismantled.

SOURCE: https://en.wikipedia.org/wiki/Communication_with_submarines#/media/File:Clam_Lake_ELF.jpg [viewed 2021-03-16]. Reproduced with permission.

Figure 12 – Aerial photograph of Clam Lake ELF facility in Wisconsin, USA (1982)

Figure 12 shows the aerial photograph of the Clam Lake ELF facility in Wisconsin, USA. Radio transmitter stations located at Clam Lake in Wisconsin and Republic, Michigan are operated and managed by NCTAMS LANT (Detachment of the Naval Computer and Telecommunications Area Master Station Atlantic) in Norfolk, Virginia. NCTMAS LANT operates in accordance with the Space and Naval Warfare Systems Command (SPAWAR) to ensure that the ELF transmission system maintains current and keeps operating at all times. SPAWAR, located in Newport, Rhode Island, is responsible for receiving, recognizing, and decrypting broadcast messages from submarines to ensure proper operation of the system.

The coding used for US Navy ELF transmissions uses a 64 symbol Reed-Solomon error correction code, each represented by a very long pseudo-random sequence. The entire transmission is encrypted. The advantage of this technique is that it can be used in associative multiple transmissions, the message can be complete even at very low SNR, and – because the actual string can be represented with very few pseudo-random sequences – if the message is received successfully, it will have a very high probability of being an effective message (anti-spoofing). Communication links are one-way, and submarines cannot mount ELF transmitters because of the vast size of the device. Attempts to design the transmitter to sink into the sea or carry it to the airplane were soon dismissed.

Due to the limited bandwidth, the information can only be transmitted at very low data rate, approximately a few characters per minute. It is reasonable to assume that the actual message is mostly a request to establish a comprehensive command or other forms of two-way communication with the appropriate authority.

5.4.2.2 ELF communication technology in Russia

The Soviet or Russian system called ZEVS operated at 82 Hz (wavelength 3 656 km). The Russian antenna (ZEVS, 82 Hz) was installed at Kola Peninsula (69 degrees north latitude, 33 degrees east longitude) northwest of Murmansk and was discovered worldwide by the radio noise measurement system operated by Stanford University in the early 1990s. An 82 Hz signal was received at a base in the Antarctic Arrival Heights (latitude 78° south, longitude 167° west).

The transmitter consists of two sinusoidal voltage swept-frequency generators and two parallel horizontal grounded antennas with a length of about 60 km. The antenna building is located in a region with less effective conductivity, the feedline and antenna end is grounded, and the ground depth signal is sent to make the Earth itself an efficient radiating element.

ZEVS uses MSK and the widest frequency observed at the beginning of the transmitted message is 81 Hz to 83,3 Hz.

5.4.2.3 ELF communication technology in India

India set up an ELF communication facility near the village of Vijaya Narayanam in Damagundam Reserve Forest for communications with the submarine in 2012 and commissioned it in 2015 and has a nuclear bunker. The Indian Navy has a VLF transmission facility of 18,2 kHz to communicate the operational ELF communication facility to the INS Kattabomman of Tirunelveli with Arihan class and Akula class submarines.

5.4.2.4 ELF communication technology in UK

The British Navy once considered and tested an ELF transmitter facility operating at 72 Hz to communicate with the Trident submarine in the Glengarry Forest in Scotland, but the project was cancelled after political disputes over cost and utility.

5.4.2.5 VLF communication technology in the US

VLF transmission stations for communicating with submarines generally have a large area (several square kilometres) and transmission power of 20 kW to 2 MW, and submarines receive signals by using a towed antenna form that floats below the surface. With this narrow bandwidth, VLF radio signals cannot carry voice, and only text messages can be transmitted at a low data rate.

The VLF data rate is about 300 bits per second or 450 words per minute with 35 8-bit ASCII characters. In general, modulation schemes used in VLF communication are OOK/CWK, FSK, and MSK. FSK has 50 bit/s and 75 bit/s speed while MSK has 300 bit/s speed.

Because of the low frequency, the VLF broadcast antenna should be very large, and the broadcast area is usually several square kilometres. This fact prevents such an antenna from being installed in a submarine. The submarine carries only a VLF receive antenna and does not respond at such low frequencies. So terrestrial-submarine VLF broadcasts are always one-way broadcasts, sent on the terrestrial, and received on the submarine. If bidirectional communication is required, the boat should rise to the periscope depth (near the surface) and telescopic mast antennas should be raised to communicate at higher frequencies (HF, UHF, or VHF).

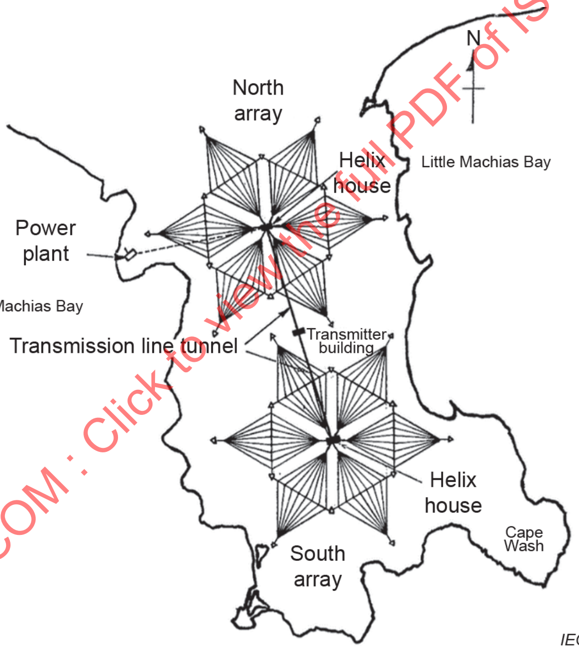
The United States operates six VLF transmitters and only a few other countries, including the UK, Germany, Italy, Australia, Norway, Japan, and India, have VLF transmitters.

The VLF transmitter, located in Cutler, Maine, USA, uses the call sign NAA to transmit at a frequency of 24 kHz, uses up to 1,8 MW of input power, and is one of the most powerful radio transmitters in the world.

This transmitter was built in 1960 and started operating in January 1961. The transmission power is 2 MW, and the transmission signal uses continuously encrypted MSK and operates at 24 kHz (operated at 17,8 kHz in the past). It has an array of 13 metal antenna columns called a trideco or umbrella antenna, as shown in Figure 13. The central antenna is 304 m high and is surrounded by six 266,7-m-high antenna columns installed in a circle of 556 m around the central tower. The Cutler antenna array and Cutler VLF antenna array are shown in Figure 14 and Figure 10, respectively.

SOURCE: https://en.wikipedia.org/wiki/VLF_Transmitter_Cutler#/media/File:Cutlervlf2.jpg [viewed 2021-03-16]. Reproduced with permission.

Figure 13 – Cutler VLF transmitter's antenna towers



SOURCE: https://en.wikipedia.org/wiki/VLF_Transmitter_Cutler#/media/File:Cutler_VLF_antenna_array_site_plan.png [viewed 2021-03-16]. Reproduced with permission.

Figure 14 – Cutler antenna array

The US Navy VLF Transmission Station in Jim Creek, near Oso, Washington, USA, was built in 1953. The transmitter operates at 24,8 kHz with a power of 1,2 MW and has a call sign NLK, and is about 2 000 ha in area in the form of a "valley-span" antenna. The antenna consists of 10 catenary shape cables (1 719 m to 2 652 m in length) and hangs in a zigzag form on twelve about 6-m-high towers above the valley between Wheeler Mountain and Blue Mountain, as shown in Figure 11.

The US Navy VLF Transmission station near Lualualei in Hawaii, USA, uses a pole (458,11 m) with two branches and operates at 21,4 kHz and 23,4 kHz (calling code NPM). Two columns of the umbrella-type antenna structure were made in 1972.

5.4.2.6 VLF communication technology in England

Anthorn Radio Station, located near Anthorn, Cumbria, UK, is operated by Babcock International and has VLF, LF, and eLORAN transmitters. The VLF transmitter of this transmission station is a NATO facility primarily used to transmit commands to the submarine at 19,6 kHz with a call sign GQD and controlled by the Northwood Headquarters with three other VLF transmitters in Norway, Germany, and Italy. The transmission station has a maximum transmission rate of 45,5 bit/s while emitting a single telegraph channel and has a power range of 50 kW in 16 kHz and 100 kW at 20 kHz.

5.4.2.7 VLF communication technology in Germany

The German VLF transmitter DHO38 is located near Rhauderfehn in Saterland, Germany, and is used to transmit encrypted commands to the German Navy and other navy submarines in NATO countries. Since 1982, it has an umbrella-type antenna structure that emits up to 800 kW of power with a signal of 23,4 kHz and has eight antenna columns (352,8 m height).

5.4.2.8 VLF communication technology in Norway

The Noviken VLF transmitter is located near Gildeskal, Norway, and is a facility used by NATO to transmit messages to submarines in the underwater environment at a frequency of 16,4 kHz (call sign JXN, 45 kW power). Three wires are twisted between two mountains, and the maximum length is 2 375 m. FSK On/Off method is used.

5.4.2.9 VLF communication technology in France

The HWU transmitter, located near Rosnay in France, is a facility to send commands to submarines in the water of the French Navy. There are 13 electric wire rods (maximum 357 m, six 310 m, six 270 m), and it emits in MSK format with a power of 400 kW at the frequencies of 18,3 kHz and 20,9 kHz.

5.4.2.10 VLF communication technology in Sweden

Varberg Radio Station at Grimeton, a VLF transmission facility in Halland, Sweden, is the only transmission station in the world that operates an Alexander alternator to rotate the armature of a radio transmitter and is classified as a World Heritage Site.

5.4.2.11 VLF communication technology in Italy

The VLF transmitter of Tavolara Island, Italy, is operated to transmit messages to submarines with frequencies of 20,27 kHz and 20,76 kHz. There is a VLF antenna with a twisted wire between the 133-m-high antenna pole of the Spalmatore di Furi and four (two of which are 114 m high) poles posted on the southern mountain.

5.4.2.12 VLF communication technology in Russia

The Vileyka VLF Transmission Station, located in the west of Vileyka in Belarus, is the forty-third communication centre of the Russian Navy. The centre of the antenna column (305 m high), which is isolated from the ground, is composed of three antenna systems and the antenna wires are connected by six grounded ring-shaped antenna columns. Three ring antenna columns have two antenna systems so that a total 15 ring-shaped antenna columns (270 m high) are installed in the facility.

5.4.2.13 VLF communication technology in Japan

Figure 15 shows the Ebino VLF transmitter, located near Miyazaki Ebino in Japan, which was installed in 1991 to send commands to the Japanese Navy submarines. It operates at 22,1 kHz frequency and has eight columns of 270 m high arranged in two rows.

SOURCE: https://en.wikipedia.org/wiki/Ebino_VLF_transmitter#/media/File:JMSDF_Ebino_VLF.JPG [viewed 2021-03-16] Reproduced with permission.

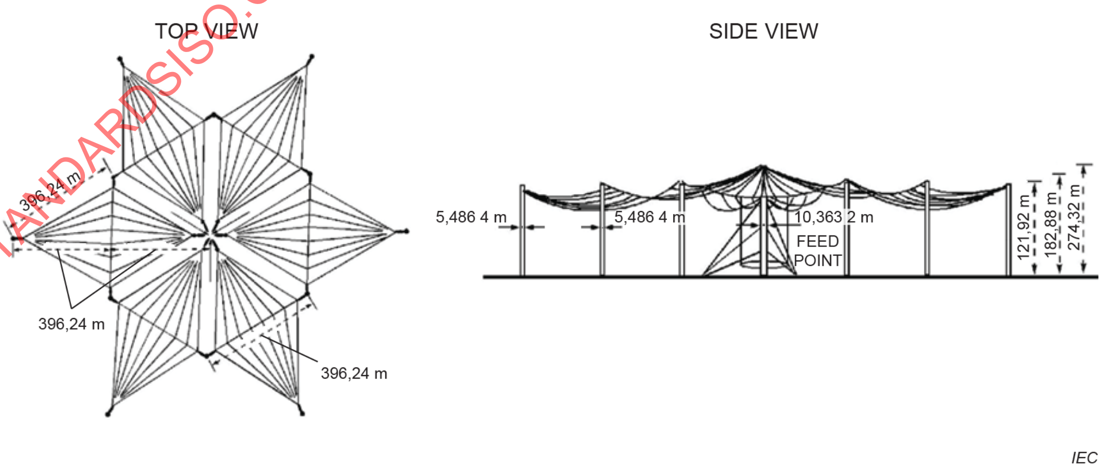
Figure 15 – VLF transmission centre in Japan

5.4.2.14 VLF communication technology in Pakistan

The PNS Hameed VLF transmitter, located near the Karachi coastal area of Sindh, Pakistan, was built in 2016 and operates at a frequency of 22,7 kHz.

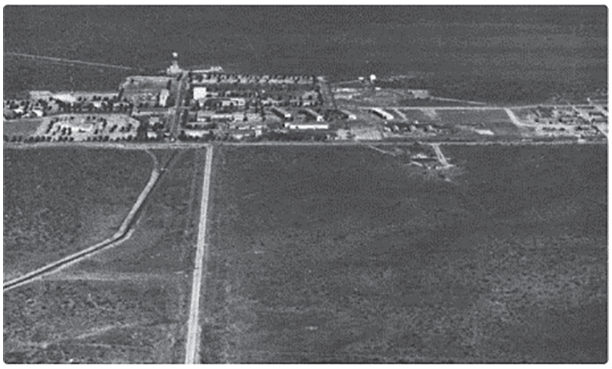
5.4.2.15 VLF communication technology in Australia

Figure 16 shows the trideco-type antenna placement in Harold E. Holt Australian Naval Service, which is located on the northwest coast of Western Australia, 6 km north of Exmouth. The town of Exmouth was built in 1963 at the same time as the Bureau of Communications to provide a base and home for the families of US Navy employees. This transmission station provides VLF radio transmission to vessels and submarines of the US Navy and the Australian Navy in the Western Pacific and the eastern Indian Ocean, and operates at 19,8 kHz with 1 MW of transmit power. This transmission station is the strongest in the Southern Hemisphere. The transmitting station has 13 wireless towers. The largest tower, called Tower Zero, is 387 m in length, and six 364 m towers form a hexagon around Tower Zero. The other six 304 m towers are located within the largest hexagon of Tower Zero. Figure 17 shows a picture of the Australian VLF transmitter.



SOURCE: https://en.wikipedia.org/wiki/Naval_Communication_Station_Harold_E._Holt#/media/File:Trideco.png [viewed 2021-03-16]. Reproduced with permission.

Figure 16 – Trideco-type antenna placement in Harold E. Holt



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SOURCE: https://en.wikipedia.org/wiki/Naval_Communication_Station_Harold_E._Holt#/media/File:US_Naval_Communication_Station_Harold_E._Holt_in_Exmouth,_Western_Australia,_c1979.jpg [viewed 2021-03-16]. Reproduced with permission.

Figure 17 – Australian VLF transmitter (1979)

5.5 Magnetic fusion communication (MFC)

5.5.1 Technical overview

5.5.1.1 Technical definition

Magnetic fusion communication (MFC) is a wireless communication technology that transmits and receives information simultaneously with wireless power transmission using magnetic field energy in a low-frequency band (30 kHz to 300 kHz). The operating centre frequency of the MFAN, which is one of magnetic fusion communications, is 128 kHz and uses BPSK modulation. Manchester coding and NRZ-L coding are used to provide data rates of several kilobits per second at distances of a few metres. The devices participating in the magnetic fusion communication system are divided into a coordinator and a node according to their roles. There is only one coordinator in one network, and a plurality of nodes form a network around the coordinator. The coordinator manages the connection and release of nodes. A magnetic fusion communication network uses a TDMA scheme, which is managed by a coordinator and distributed according to the request of the nodes and the decision of the coordinator. Communication between nodes is also possible for relay communication or peer-to-peer (P2P) communication for network extension. This can be applied to sensor networks, home networks, and application services such as construction, agriculture, traffic, and underwater [100].

5.5.1.2 Characteristic of technology

In this region, since the intensity of the magnetic field is very strong compared with the intensity of the electric field, the strength of the electric field cannot be greatly affected, and this region has a strong characteristic of the magnetic field. The magnetic fusion communication technology uses a loop antenna to emit low-frequency signals and communicate within the magnetic field range, enabling unrestricted communication in water, underground, and in air. Besides, since low frequencies are used, it can be utilized as a communication technology that can exceed the limit of a specific medium, such as providing excellent communication performance compared to the existing electromagnetic wave method even when passing through metal [101].

The centre frequency (f_c) of the MFAN, which is one of the magnetic fusion communications, is 128 kHz, and the maximum tolerance of the centre frequency is 128 kHz ± 2,56 Hz. The converted bit signals according to the definitions of the physical layer, packet format, coding, and modulation are made into the envelope defined in Figure 18 and Table 1 [8]. The magnitude of the envelope size can be divided into the positive change magnitude (M_h) and the negative change magnitude (M_l). The maximum value of M_h and M_l is within 10 % of A. The envelope rise time (t_r) is the time it takes to rise from 10 % of A to 90 % of A and the envelope fall time (t_f) is the time it takes to drop from 90 % of A to 10 % of A. The bit interval (T bits) depends on the data rate, and t_r and t_f do not exceed 30 % of the T bits.

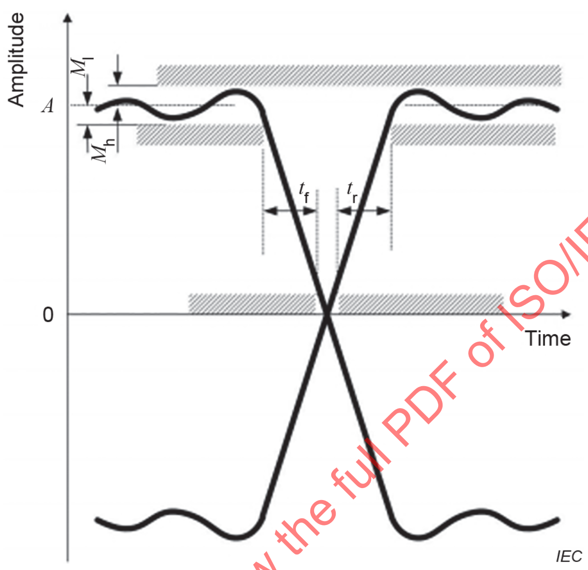

Figure 18 – Shape of envelope

Table 1 – Envelope parameters

Parameters	Symbol	Minimum	Maximum
Positive variation	M_h	0	0,1 A
Negative variation	M_l	0	0,1 A
Rise time	t_r	0	0,3T bit
Fall time	t_f	0	0,3T bit

Communication between the coordinator and the node uses BPSK modulation as shown in Figure 19 [8]. Therefore, the signal transmitted to the antenna is a BPSK modulated signal according to the envelope defined [102].

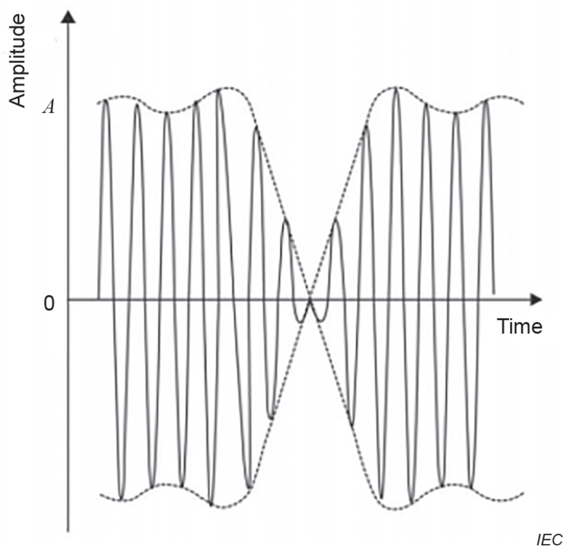

Figure 19 – BPSK modulated signal

5.5.1.3 Background

In the late 2000s, as the market for various types of mobile devices grew rapidly, market demand for the magnetic fusion communication technology increased. However, the technology related to magnetic fusion communication was not developed enough to satisfy market demand. Conventional Radio-Frequency Identification (RFID) or ubiquitous sensor network (USN) technology has difficulty in transmitting data collected from a sensor used mainly in a harsh environment due to a short data transmission distance or a large influence of surrounding obstacles. Therefore, the magnetic fusion communication technology which is extended to the transmission distance and robust to the surrounding obstacles (water, soil, metal) has appeared.

The magnetic fusion communication technology is expected to be able to transmit data wirelessly around water, soil, and metal, and simultaneously transmit power wirelessly, so that it can be effectively applied to wireless charging products for various kinds of mobile electronic devices. In particular, the magnetic resonance wireless power transfer technology for magnetic resonant coupling method can wirelessly transmit power to multiple mobile devices within a few centimetres to several metres and this technology has the advantage of charging the sensor device at a distance from the ground or underwater, or charging several sensor devices at the same time [103].

5.5.1.4 Technology classification

5.5.1.4.1 General

Magnetic fusion communication technology can be broadly divided into magnetic field communication technology and wireless power transmission technology. An overview of each technology is provided in 5.5.1.4.2 and 5.5.1.4.3, respectively.

5.5.1.4.2 Overview of magnetic field communication technology

Magnetic field communication technology is a wireless communication system that uses a magnetic field area and enables wireless communication in extreme environments such as metal, underwater, underground, and collapse of the building. The basic components of magnetic field communication technology are physical layer protocol and system technology, and medium access control layer protocol and system technology. Unlike commonly used high-frequency communication technologies, low frequency is used because it has high permeability and low propagation loss when passing through different mediums such as soil, water and concrete [104].

5.5.1.4.3 Overview of wireless power transmission technology

Wireless power transmission technology is a technology that can transmit and receive power wirelessly by applying the principle of magnetic field communication. This technique is largely divided into a magnetic inductive coupling method and a magnetic resonant coupling method. The magnetic inductive coupling method can transmit several milliwatts to several tens of kilowatts; the transmission distance depends on the transmission capacity, but it is limited to a few centimetres or less for several hundred watts or less. Unlike the magnetic inductive coupling method, the magnetic resonance coupling method can transmit electric power of several watts to 1 kW over several tens of centimetres to several metres [105].

5.5.2 Trend of technology (modern communication trends)

5.5.2.1 Magnetic field communication technology

5.5.2.1.1 General

Wireless communication using the magnetic field region is less influenced by the surrounding obstacles than wireless communication using the high-frequency region. Figure 20 shows the comparison between magnetic field communication using a 128 kHz frequency band and Zigbee™[4] communication using a 2,4 GHz frequency band [8].

The magnetic field communication system and the Zigbee communication system were buried in the ground and experiments were conducted on three cases. The results are shown in Figure 20. Case 1 shows data transmission in the air at a distance of 70 cm, Case 2 shows data transmission at 25 cm above the ground when the antenna is covered with 25 cm thickness of soil and Case 3 shows data transmission directly above the ground when the antenna is covered with 50 cm thickness of soil.

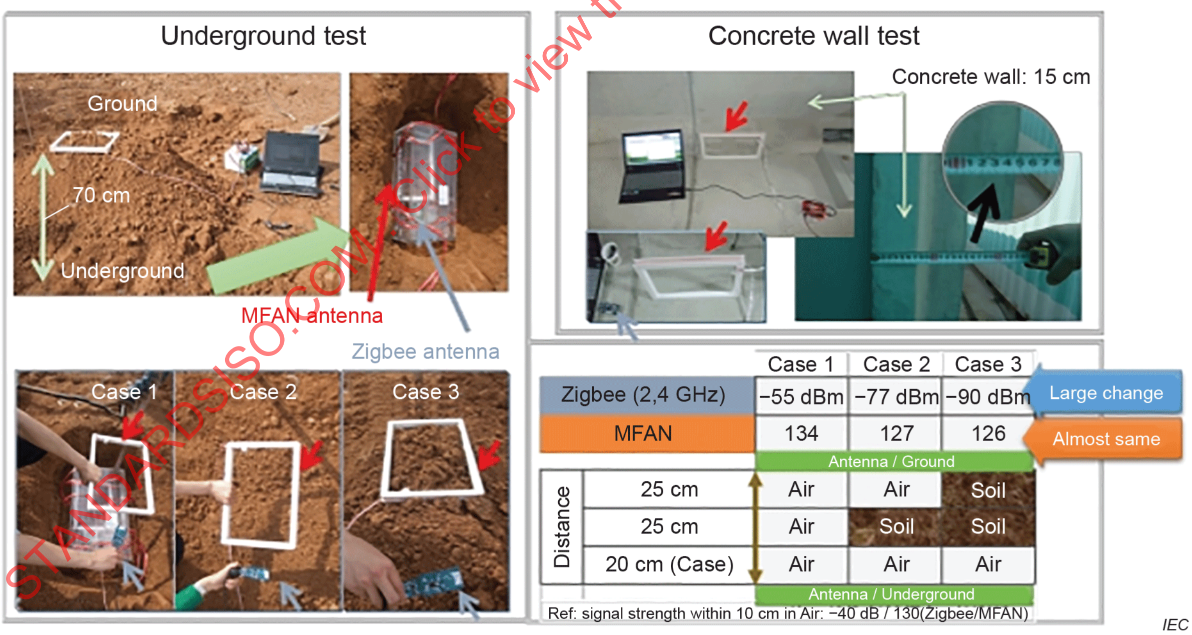

Figure 20 – Magnetic field communication and Zigbee communication comparison experiment

4 Zigbee™ is is the trade name of a product supplied by the Zigbee Alliance. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC or ISO of the product named.

Comparing the three cases, the strength of the signal is not significantly different depending on the type of medium in the case of magnetic field communication, but the intensity of the signal is significantly different depending on the thickness and type of the medium in Zigbee communication. Since the wireless communication using the magnetic field area has less influence on soil than wireless communication using the high-frequency area, it can highly be utilized as a method of communication in the field.

In wireless communication using the magnetic field area, a water tank is used as shown in Figure 21 to compare the change of the signal intensity according to the medium and the distance [8]. In the middle of the water tank, there is space for installing the communication system.

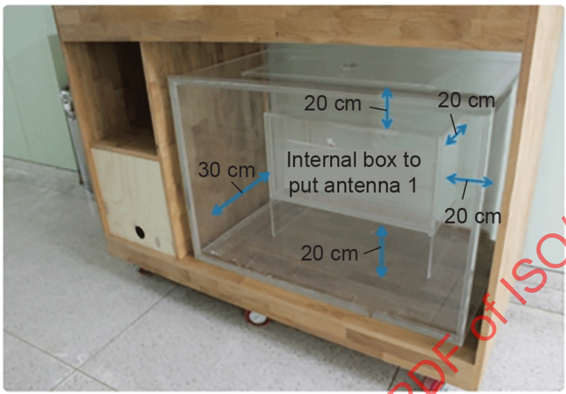

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Figure 21 – Experimental water tank for comparing magnetic field communication characteristics according to medium and distance

Figure 22 shows an experimental device for measuring magnetic field characteristics in air, water, and soil using a water tank filled with water and soil [8].

IEC

Figure 22 – Experimental water tank filled with water and soil

Table 2 gives the strength of the magnetic field according to medium and transmission distance in a water tank filled with air, water, and soil.

Table 2 – Intensity of magnetic field due to distance in air, water, and soil

	Signal strength (based on 30 cm distance)				Signal strength (based on 5 cm distance)			
Distance (cm)	30	60	90	120	30	60	90	120
Air	1,000	0,484	0,168	0,076	0,989	0,479	0,166	0,075
Soil	1,000	0,482	0,174	0,076	0,986	0,475	0,172	0,075
Water	1,000	0,457	0,154	0,072	0,985	0,450	0,152	0,071

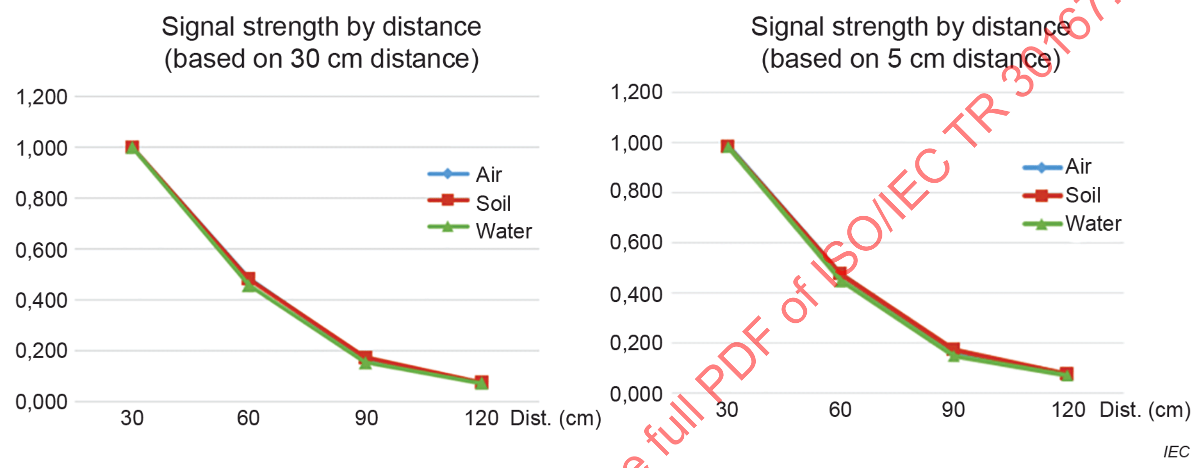


Figure 23 – Strength of magnetic field due to distance in air, water, and soil

The strength of the magnetic field decreases in proportion to the increase of the transmission distance regardless of the surrounding environment – air, water, or soil – as shown in Figure 23 [8].

5.5.2.1.2 Physical layer protocol

Figure 24 shows the physical layer packet format, which consists of a preamble, a header, and a payload [8]. Packets are sent in the preamble, header, and payload order. The packet is transmitted from the LSB [103].

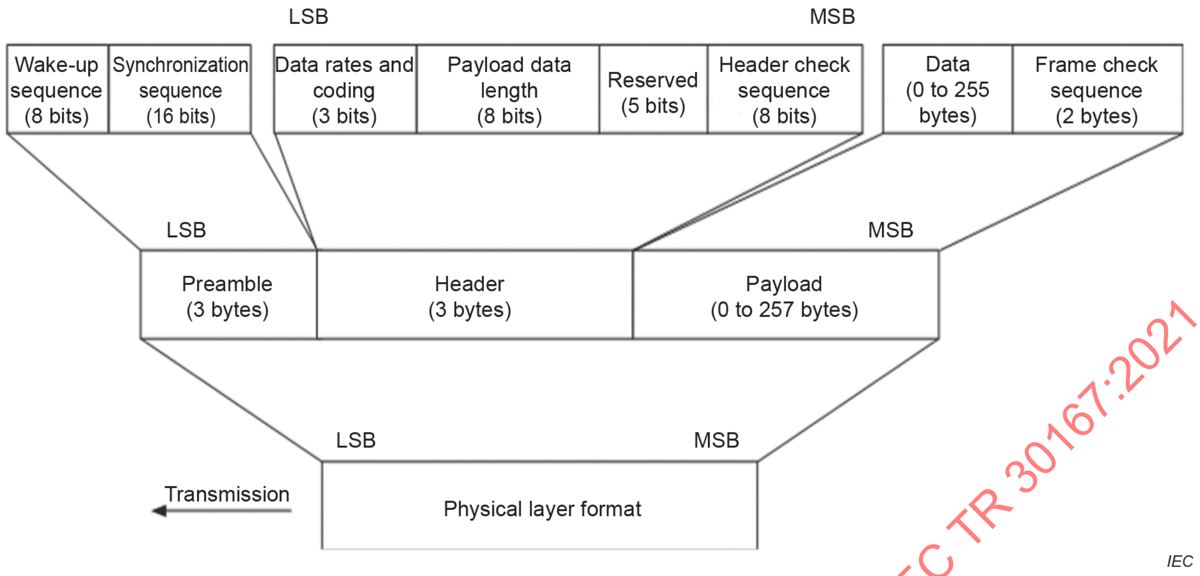


Figure 24 – Physical layer packet format

The preamble includes two parts: an 8-bit wake-up sequence [0000 0000] and a 16-bit synchronization sequence made up of 12 bits [0000 0000 0000] and 4 bits [1010], as shown in Figure 25 [8]. The wake-up sequence is included only in the preamble of the response-receiving packet in the response period. Synchronization sequences are used at the receiving end for packet synchronization, symbol time adjustment, and so on. The preamble is coded by TYPE 0 scheme.

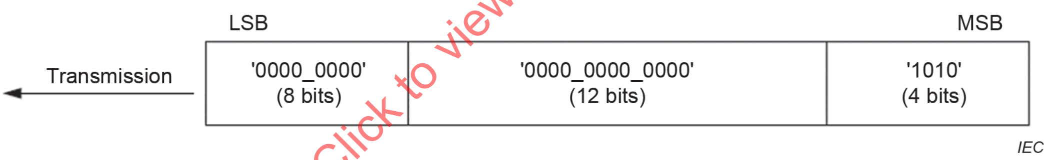


Figure 25 – Preamble area type

The header consists of two data areas – data rates and coding, and payload data length – and an 8-bit header check sequence as shown in Figure 26 [8]. Since the header is transmitted from the LSB, the LSB of the data rate and coding is transmitted first, and the MSB of the header check sequence is transmitted last. The header is coded using the TYPE 0 scheme.

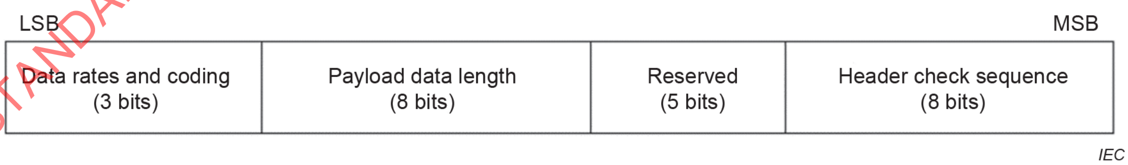


Figure 26 – Header area type

Table 3 – Definition of data rate and coding

Type	Value (b2b1b0)	Data rate	Coding method
TYPE 0	000	1 kbit/s	Manchester
TYPE 1	001	2 kbit/s	Manchester
TYPE 2	010	4 kbit/s	Manchester
TYPE 3	011	2 kbit/s	NRZ-L + Scrambling
TYPE 4	100	4 kbit/s	NRZ-L + Scrambling
TYPE 5	101	8 kbit/s	NRZ-L + Scrambling
TYPE 6	110	Reserved	-
TYPE 7	111	Reserved	-

This specifies the data rate and coding scheme applied to the payload region of the packet. Eight data rates and coding methods are defined and expressed in 3 bits as shown in Table 3.

The payload data length field has a total of 8 bits. The payload data length indicates the number of data of the current packet payload in bytes. The payload data length is from 0 bytes to a maximum of 255 bytes.

The header of the physical layer packet checks the error using the header check sequence. The header check sequence is generated using an 8-bit CRC, and the primitive polynomial for this is given as follows.

$$g(D) = (1 + D)(1 + D^2 + D^3 + D^4 + D^7) = 1 + D + D^2 + D^5 + D^7 + D^8$$

Figure 27 shows an example of a coding circuit of a header check cyclic redundancy code [8]. The initial value of the register of the encoding circuit is set to [0000 0000], and the data is inputted while the switch S is '1'. When the last bit is inputted, S is changed to '2' to transmit the check sequence from the register. At this time, the transmission starts with the value stored in D^7.

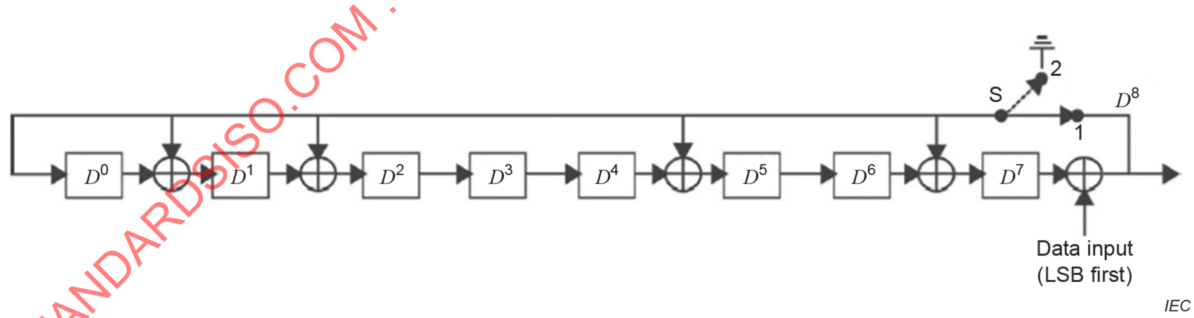


Figure 27 – Encoding circuit of header check cyclic redundancy code

Figure 28 shows the payload area format, which is composed of data to be transmitted and a frame check sequence added for checking errors therefrom [8]. When the length of the data is 0, the frame check sequence is not included. Therefore, the length of the payload is 0 to 257 bytes.

Figure 28 – Payload area format

The frame check sequence is generated using a 16-bit cyclic redundancy code. The frame check sequence is calculated for the payload data area and is not generated if the payload data length is zero. The frame check sequence is calculated in accordance with Table 4, and then it is replaced with 1's complement and sent after the data.

Table 4 – Definition of frame check cyclic redundancy code

CRC type	Length	Polynomial	Preset	Residue
ISO/IEC 13239	16 bit	$X^{16} + X^{12} + X^5 + 1$	0xFFFF	0x1D0F

The Manchester coding changes the signal level in the middle of each bit interval (T_{bit}). In this case, the level changes from level '1' to level '0' when the data bit is '0', and from level '0' to level '1' when the data bit is '1' as shown in Figure 29 [8].

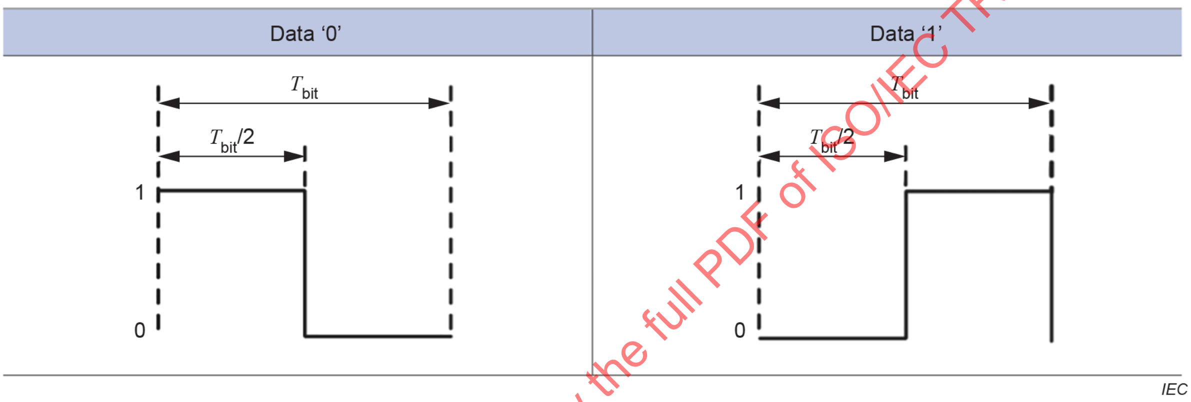


Figure 29 – Definition of Manchester coding

NRZ-L is matched to level '0' when the data bit is '0' and to level '1' when the data bit is '1'.

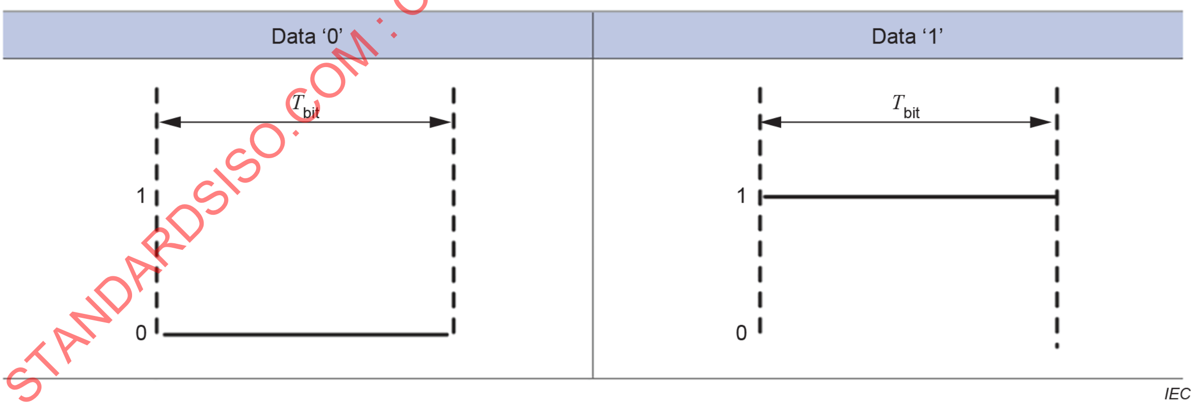


Figure 30 – Definition of NRZ-L coding

Figure 30 shows the definition of NRZ-L coding [8]. The payload of a packet coded in the NRZ-L scheme is scrambled through a scrambler. The preamble and header are not scrambled. The primitive polynomial g(D) of the scrambler is as follows.

$$g(D) = 1 + D^{14} + D^{15}$$

At this time, D is a bit delay element. d_k is created as follows.

$$d_k = d_{k\text{-}14} \oplus d_{k\text{-}15}$$

Figure 31 shows the scrambler block diagram [8]. At this time, it is an exclusive OR. The initial value of the polynomial is all 1s. If the data input s_k is a bit before being scrambled, the scrambled data output b_k is given by the following equation.

$$b_k = s_k \oplus d_k$$

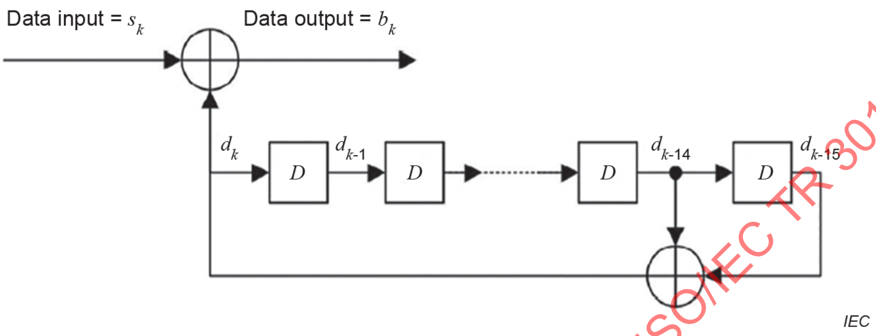


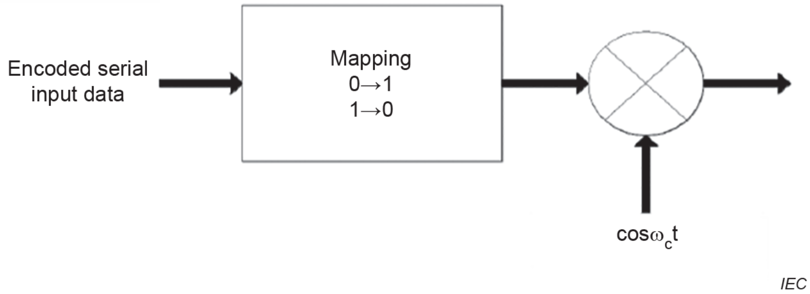
Figure 31 – Scrambler block diagram

The physical layer defines the data rate and coding scheme as shown in Table 5. TYPE 0, TYPE 1, TYPE 2 use Manchester coding, and the data rates are 1 kbit/s, 2 kbit/s, and 4 kbit/s, respectively. TYPE 3, TYPE 4, and TYPE 5 are scrambled after NRZ-L coding. The data rates are 2 kbit/s, 4 kbit/s, and 8 kbit/s, respectively. The preamble and header are Manchester coding according to the TYPE 0 scheme and are transmitted at 1 kbit/s. In the payload, the data rate and coding scheme are selected based on the current channel status. The data rate and coding scheme of the payload are specified in the header of the packet to be transmitted.

Table 5 – Data rate and coding details

Type	Data rate	Coding method	Note
TYPE 0	1 kbit/s	Manchester	-
TYPE 1	2 kbit/s	Manchester	-
TYPE 2	4 kbit/s	Manchester	-
TYPE 3	2 kbit/s	NRZ-L + Scrambling	-
TYPE 4	4 kbit/s	NRZ-L + Scrambling	-
TYPE 5	8 kbit/s	NRZ-L + Scrambling	-
TYPE 6	Reserved	-	-
TYPE 7	Reserved	-	-

Communication between the coordinator and the node can be done using ASK modulation or BPSK modulation as shown in Figure 32 and Figure 33 [8]. Encrypted repetitive input data is transformed into ASK points.



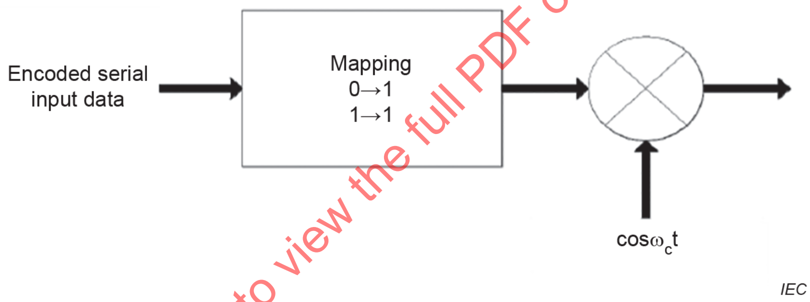
Key

ω_c carrier frequency

t time

Figure 32 – ASK modulation diagram

The communication between the coordinator and the node uses a BPSK modulation scheme. The signal converted into each TYPE I (I = 0 to 7) is transmitted through a pulse waveform. Here, f_c is the centre frequency of the magnetic fusion communication.



Key

ω_c carrier frequency

t time

Figure 33 – BPSK modulation diagram

This defines a series of processes for coding and modulating the information for each of the preamble, header, and payload of the packet.

The preamble uses a 16-bit sequence and TYPE 0. The wake-up sequence is modulated by the synchronization sequence of ASK and BPSK as shown in Figure 34 [8].

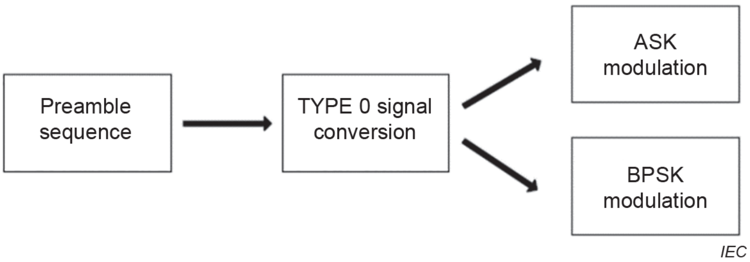


Figure 34 – Preamble coding and modulation process