



BSI Standards Publication

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

National foreword

This Published Document is the UK implementation of ISO/IEC TR 30167:2021.

The UK participation in its preparation was entrusted to Technical Committee IOT/1, Internet of Things.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

This publication is not to be regarded as a British Standard.

© The British Standards Institution 2021
Published by BSI Standards Limited 2021

ISBN 978 0 539 14537 3

ICS 35.110; 33.020

Compliance with a Published Document cannot confer immunity from legal obligations.

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 July 2021.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

TECHNICAL REPORT



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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 33.020

ISBN 978-2-8322-9865-7

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD.....	4
INTRODUCTION.....	5
1 Scope.....	6
2 Normative references	6
3 Terms and definitions	6
4 Symbols and abbreviated terms.....	6
5 Enabling/driving technologies of underwater communication.....	7
5.1 General.....	7
5.2 Acoustic communication.....	8
5.2.1 Technical overview	8
5.2.2 Trend of technology (modern communication trends).....	14
5.3 Optical (wire/wireless) communication	21
5.3.1 Technical overview	21
5.3.2 Trend of technology (modern communication trends).....	24
5.4 Very Low Frequency (VLF)/Extremely Low Frequency (ELF).....	28
5.4.1 Technical overview	28
5.4.2 Trend of technology (modern communication trends).....	31
5.5 Magnetic fusion communication (MFC).....	39
5.5.1 Technical overview	39
5.5.2 Trend of technology (modern communication trends).....	42
Bibliography.....	54
Figure 1 – Example of underwater acoustic sensor network system	8
Figure 2 – Path loss of sound wave	10
Figure 3 – Multipath of sound wave.....	10
Figure 4 – Terrestrial/underwater interworking gateway	13
Figure 5 – Underwater cable structure	21
Figure 6 – Fibre-optic wired communication system overview	21
Figure 7 – Current underwater cable map	23
Figure 8 – Optical wired communication system overview	25
Figure 9 – Optical wired communication system based on WDM technology	25
Figure 10 – Trideco antenna tower array used in the US Navy's Cutler station.....	29
Figure 11 – Valley-span antenna type used by the US navy station, Jim Creek	29
Figure 12 – Aerial photograph of Clam Lake ELF facility in Wisconsin, USA (1982)	34
Figure 13 – Cutler VLF transmitter's antenna towers.....	36
Figure 14 – Cutler antenna array	36
Figure 15 – VLF transmission centre in Japan	38
Figure 16 – Trideco-type antenna placement in Harold E. Holt.....	38
Figure 17 – Australian VLF transmitter (1979).....	39
Figure 18 – Shape of envelope	40
Figure 19 – BPSK modulated signal.....	41
Figure 20 – Magnetic field communication and Zigbee communication comparison experiment.....	42

Figure 21 – Experimental water tank for comparing magnetic field communication characteristics according to medium and distance	43
Figure 22 – Experimental water tank filled with water and soil.....	43
Figure 23 – Strength of magnetic field due to distance in air, water, and soil	44
Figure 24 – Physical layer packet format.....	45
Figure 25 – Preamble area type	45
Figure 26 – Header area type	45
Figure 27 – Encoding circuit of header check cyclic redundancy code.....	46
Figure 28 – Payload area format.....	46
Figure 29 – Definition of Manchester coding	47
Figure 30 – Definition of NRZ-L coding	47
Figure 31 – Scrambler block diagram.....	48
Figure 32 – ASK modulation diagram.....	49
Figure 33 – BPSK modulation diagram.....	49
Figure 34 – Preamble coding and modulation process	49
Figure 35 – Process of coding and modulating headers	50
Figure 36 – Process of coding and modulating the payload.....	50
Figure 37 – Magnetic fusion communication super frame structure	50
Figure 38 – Magnetic field communication network structure.....	51
Figure 39 – Magnetic fusion (power transfer) communication network super-frame structure	52
Figure 40 – Magnetic fusion (power transfer) communication network structured diagram	53
Table 1 – Envelope parameters	40
Table 2 – Intensity of magnetic field due to distance in air, water, and soil.....	44
Table 3 – Definition of data rate and coding.....	46
Table 4 – Definition of frame check cyclic redundancy code.....	47
Table 5 – Data rate and coding details.....	48

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

FOREWORD

- 1) ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work.
- 2) The formal decisions or agreements of IEC and ISO on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC and ISO National bodies.
- 3) IEC and ISO documents have the form of recommendations for international use and are accepted by IEC and ISO National bodies in that sense. While all reasonable efforts are made to ensure that the technical content of IEC and ISO documents is accurate, IEC and ISO cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC and ISO National bodies undertake to apply IEC and ISO documents transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC and ISO document and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC and ISO do not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC and ISO marks of conformity. IEC and ISO are not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this document.
- 7) No liability shall attach to IEC and ISO or their directors, employees, servants or agents including individual experts and members of its technical committees and IEC and ISO National bodies for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this ISO/IEC document or any other IEC and ISO documents.
- 8) Attention is drawn to the Normative references cited in this document. Use of the referenced publications is indispensable for the correct application of this document.
- 9) Attention is drawn to the possibility that some of the elements of this ISO/IEC document may be the subject of patent rights. IEC and ISO shall not be held responsible for identifying any or all such patent rights.

ISO/IEC TR 30167 has been prepared by subcommittee 41: Internet of Things and Digital Twin, of IEC joint technical committee 1: Information technology. It is a Technical Report.

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.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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.

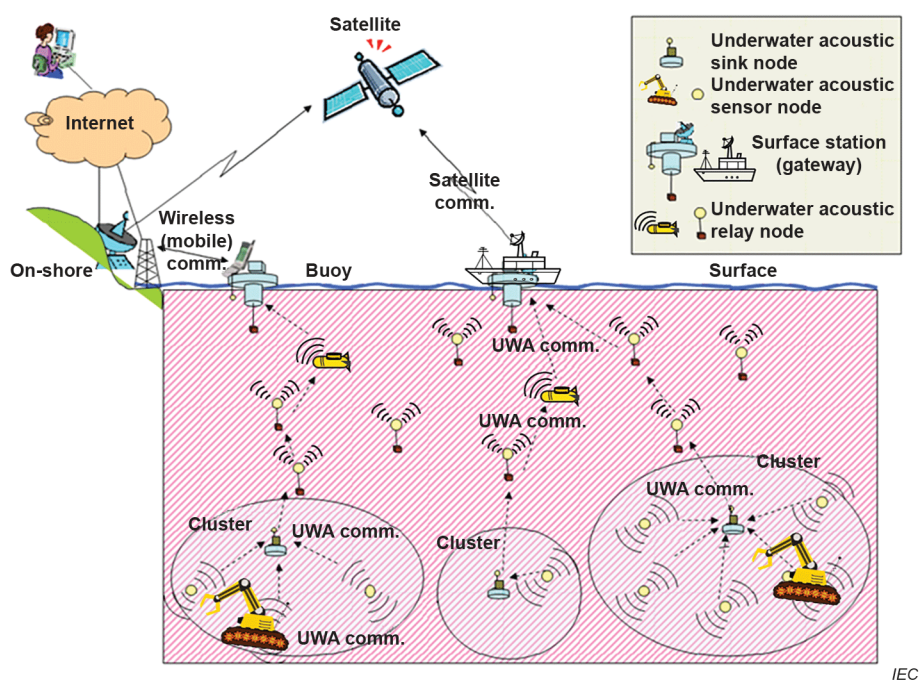
5.2 Acoustic communication

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].

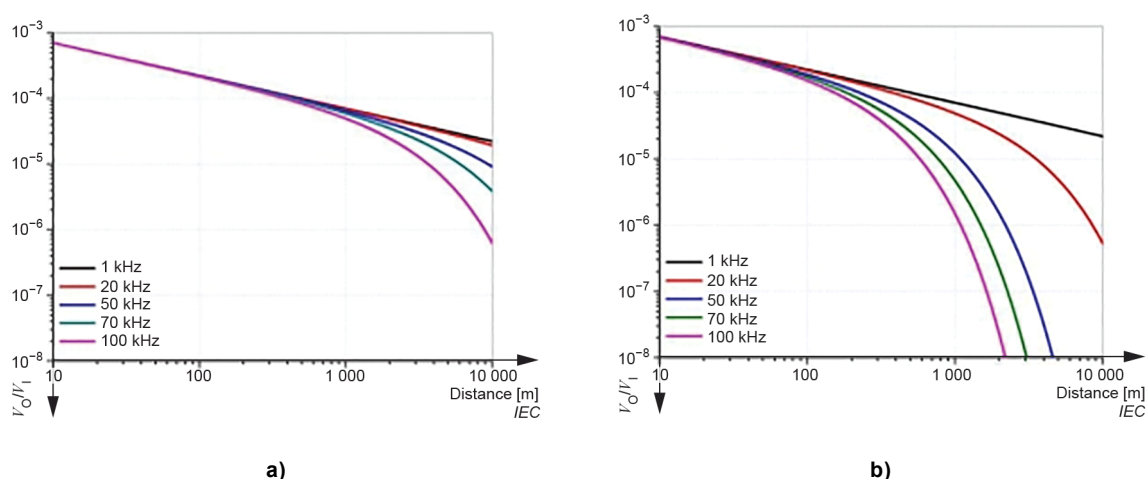
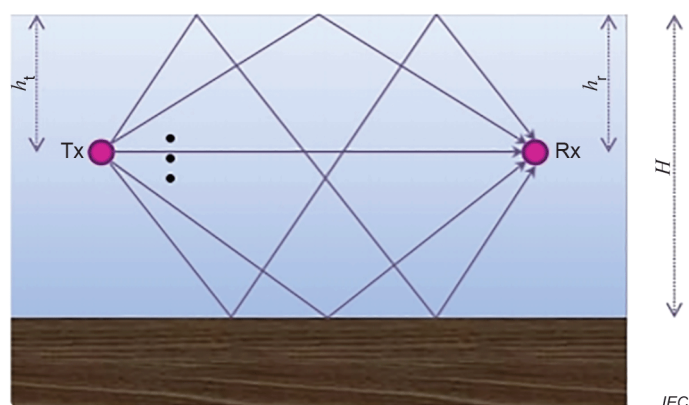


Figure 2 – Path loss of sound wave

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.

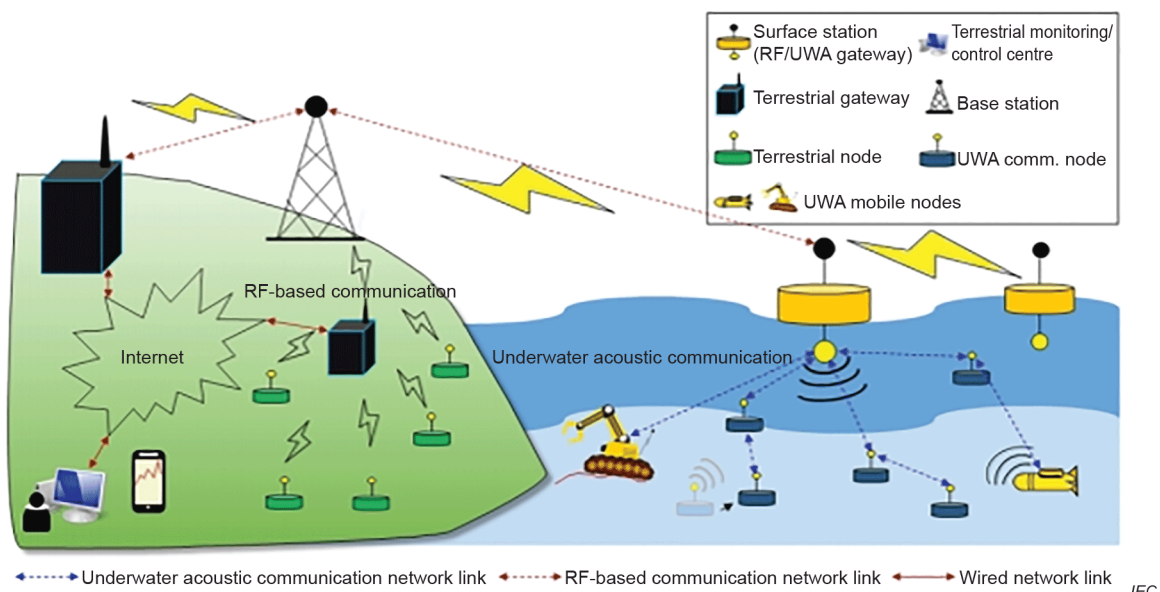


Figure 4 – Terrestrial/underwater interworking gateway

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 reducing 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.