ISO/IEC TR 30167

Edition 1.0 2021-06

TECHNICAL REPORT

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

ISO/IEC TR 30167:2021-06(en)

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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 33.020

ISBN 978-2-8322-9865-7

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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.

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- IEC Electropedia: available at http://www.electropedia.org/
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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.

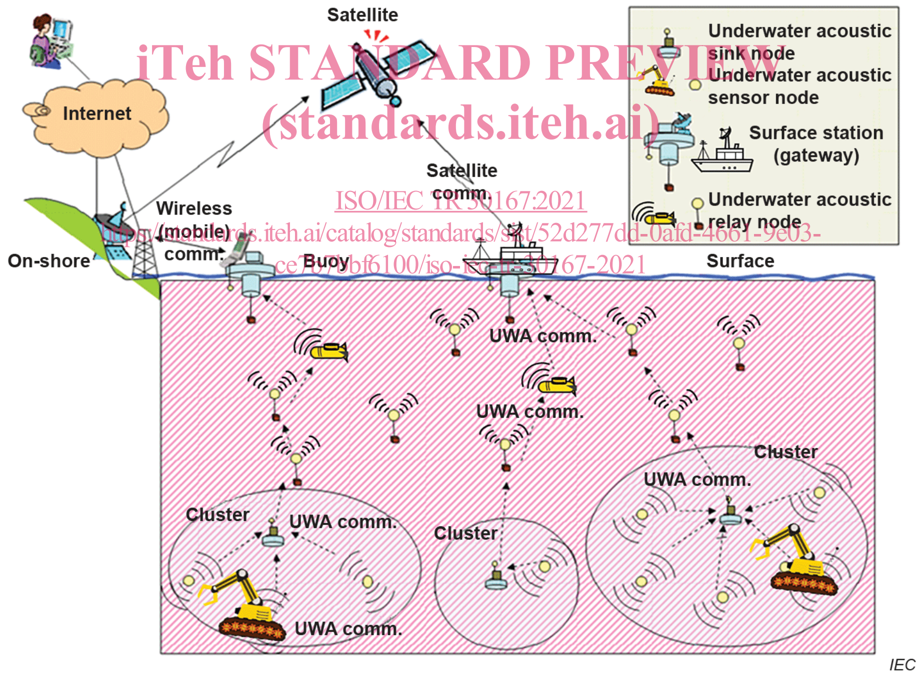
5.2 Acoustic communication

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].

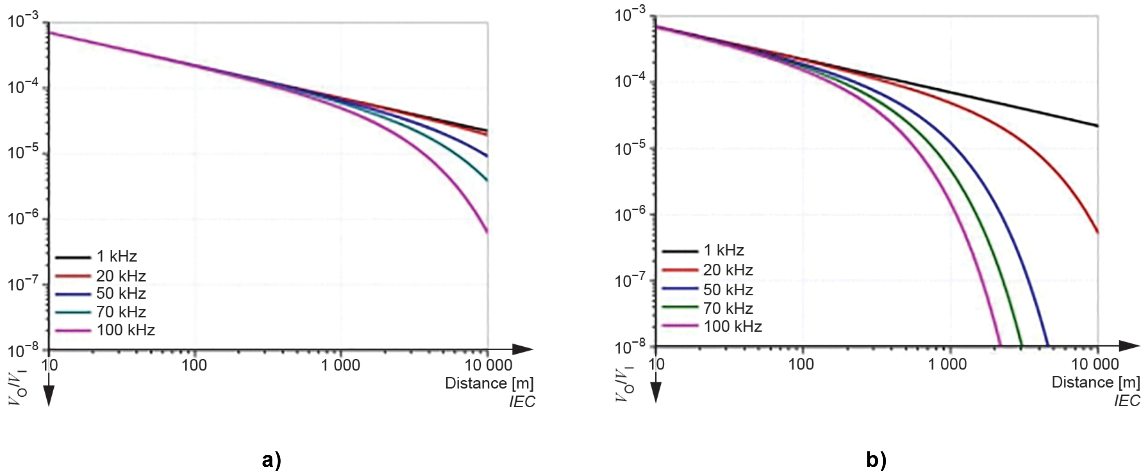
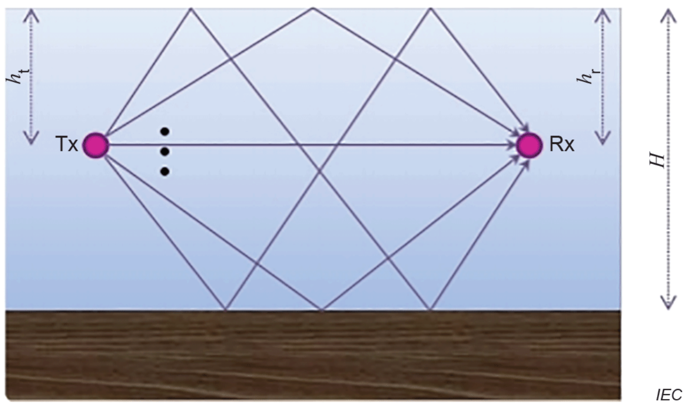


Figure 2 – Path loss of sound wave

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.

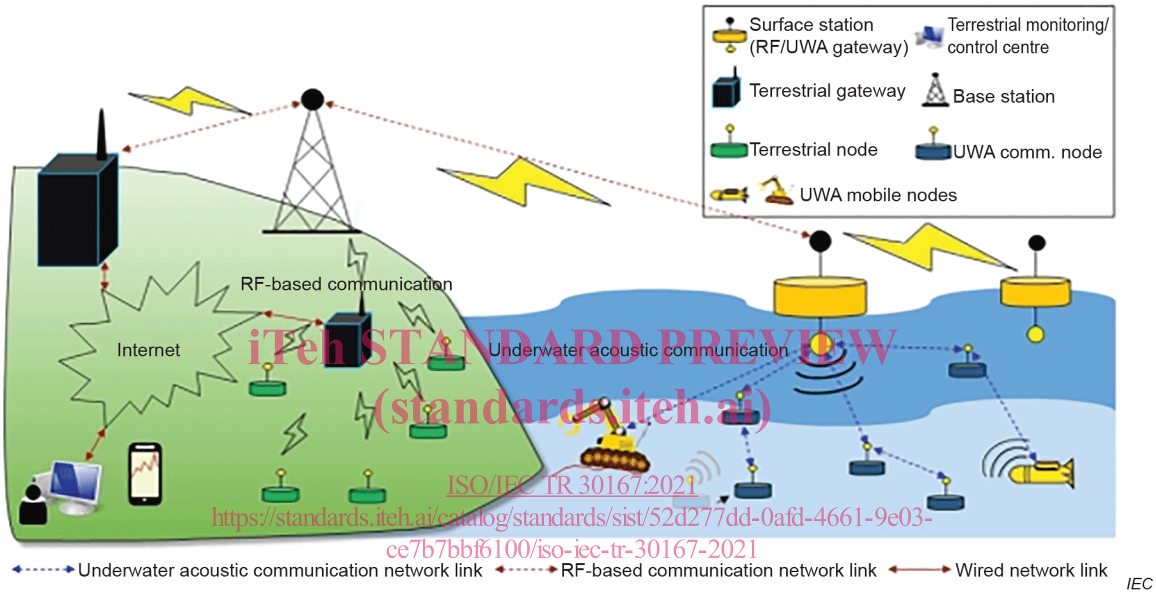


Figure 4 – Terrestrial/underwater interworking gateway

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.