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Information technology – Underwater acoustic sensor network (UWASN) – Part 1: Overview and requirements

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INFORMATION TECHNOLOGY – UNDERWATER ACOUSTIC SENSOR NETWORK (UWASN) –

Part 1: Overview and requirements

FOREWORD

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International Standard ISO/IEC 30140-1 was prepared by subcommittee 41: Internet of Things and related technologies, of ISO/IEC joint technical committee 1: Information technology.

The list of all currently available parts of the ISO/IEC 30140 series, under the general title *Information technology – Underwater acoustic sensor network (UWASN)*, can be found on the IEC and ISO websites.

This International Standard has been approved by vote of the member bodies, and the voting results may be obtained from the address given on the second title page.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

INTRODUCTION

Water covers approximately 71 % of the surface of the Earth. Modern technologies introduce new methods to monitor the body of water, for example pollution monitoring and detection. Underwater data gathering techniques require exploring the water environment, which can be most effectively performed by underwater acoustic sensor networks (UWASNs). Applications developed for the UWASNs can record underwater climate, detect and control water pollution, monitor marine biology, discover natural resources, detect pipeline leakages, monitor and locate underwater intruders, perform strategic surveillance, and so on.

The ISO/IEC 30140 series provides general requirements, reference architecture (RA) including the entity models and high-level interface guidelines supporting interoperability among UWASNs in order to provide the essential UWASN construction information to help and guide architects, developers and implementers of UWASNs.

Additionally, the ISO/IEC 30140 series provides high-level functional models related to underwater sensor nodes and relationships among the nodes to construct architectural perspective of UWASNs. However, the ISO/IEC 30140 series is an application agnostic standard. Thus, ISO/IEC 30140 series specifies neither any type of communication waveforms for use in UWASNs nor any underwater acoustic communication frequencies. Specifying communication waveforms and/or frequencies are the responsibility of architects, developers and implementers.[1]

Acoustical data communication in sensor networks necessitates the introduction of acoustical signals that overlap biologically important frequency bands into the subject environment. These signals may conflict with regional, national, or international noise exposure regulations. Implementers of acoustical communication networks should consult the relevant regulatory agencies prior to designing and deployment of these systems to ensure compliance with regulations and avoid conflicts with the agencies.

The purpose of the ISO/IEC 30140 series is to provide general requirements, guidance and facilitation in order for the users of the ISO/IEC 30140 series to design and develop the target UWASNs for their applications and services.

The ISO/IEC 30140 series comprises four parts as shown below.

Part 1 provides a general overview and requirements of the UWASN reference architecture.

Part 2 provides reference architecture models for UWASN.

Part 3 provides descriptions for the entities and interfaces of the UWASN reference architecture.

Part 4 provides information on interoperability requirements among the entities within a UWASN and among various UWASNs.

1 Architects, developers and implementers need to be aware of the submarine emergency frequency band, near and below 12 kHz, and it is recommended to provide a provision for such submarine emergency band in their UWASN design and applications.

INFORMATION TECHNOLOGY – UNDERWATER ACOUSTIC SENSOR NETWORK (UWASN) –

Part 1: Overview and requirements

1 Scope

This part of ISO/IEC 30140 provides a general overview of underwater acoustic sensor networks (UWASN). It describes their main characteristics in terms of the effects of propagation variability and analyses the main differences with respect to terrestrial networks. It further identifies the specificities of UWASN and derives some specific and general requirements for these networks.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 29182-2, *Information technology – Sensor networks: Sensor Network Reference Architecture (SNRA) – Part 2: Vocabulary and terminology*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC 29182-2 and the following apply.

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

3.1
ad-hoc node
device in a wireless ad-hoc network

Note 1 to entry: A wireless ad-hoc network is defined in ISO/IEC 27033-6:2016[1],[2] 3.12, as a "decentralized wireless network which does not rely on a pre-existing infrastructure".

3.2
cross-layer
technology that permits communication between different layers by allowing one layer to access data of another layer to exchange information and enable interaction

3.3
management cross-layer
technology that provides a system-level management service to all or selected OSI layers in a wireless network system

2 Numbers in square brackets refer to the Bibliography.

Note 1 to entry: Examples of management cross-layer are device management cross-layer, network management cross-layer, QoS management cross-layer, security management cross-layer, localization management cross-layer, power management cross-layer, etc.

3.4
underwater acoustic fundamental network
UWA-FN
wireless communication network that is built either exclusively using one or more cluster networks or exclusively using one or more ad-hoc networks for underwater environment using acoustic modems

Note 1 to entry: Fundamental network consists of only one network type, either cluster network or ad-hoc network.

Note 2 to entry: Wireless acoustic communication and data links are realized using an acoustic modem.

Note 3 to entry: A modem is defined in ISO/IEC 2382:2015[2], 2124386, as a “functional unit that modulates and demodulates signals”.

3.5
underwater acoustic united network
UWA-UN
wireless communication network that is made of two or more underwater acoustic fundamental networks (3.4) and relay nodes

Note 1 to entry: A relay node is, for example, an unmanned underwater vehicle, communication node, beacon, etc.

3.6
underwater acoustic extended united network
UWA-EUN
wireless communication network that is made of two or more underwater acoustic united networks (3.5)

3.7
underwater acoustic sensor node
UWA-SNode
sensor network element that includes at least one sensor and, optionally actuators with communication capabilities and data processing capabilities, which is built for underwater applications using acoustic modem as a communication unit internal to this element

Note 1 to entry: Wireless acoustic communication and data links are realized using an acoustic modem.

Note 2 to entry: A modem is defined in ISO/IEC 2382:2015, 2124386, as a “functional unit that modulates and demodulates signals”.

[SOURCE: ISO/IEC 29182-2:2013, 2.1.8 – modified: the original definition of sensor node is adapted to an underwater acoustics context.]

3.8
underwater acoustic cluster head
UWA-CH
unit that receives data from underwater acoustic sensor nodes (3.7) and transmits the data to one or more relay nodes or a nearby underwater acoustic gateway (3.9)

3.9
underwater acoustic gateway
UWA-GW
unit connecting different underwater networks or parts of one underwater network and performing any necessary protocol translation in underwater environment using acoustic modem

[SOURCE: ISO/IEC TR 29108:2013, 3.1.88.3 – modified: the original definition is adapted to an underwater acoustics context.]

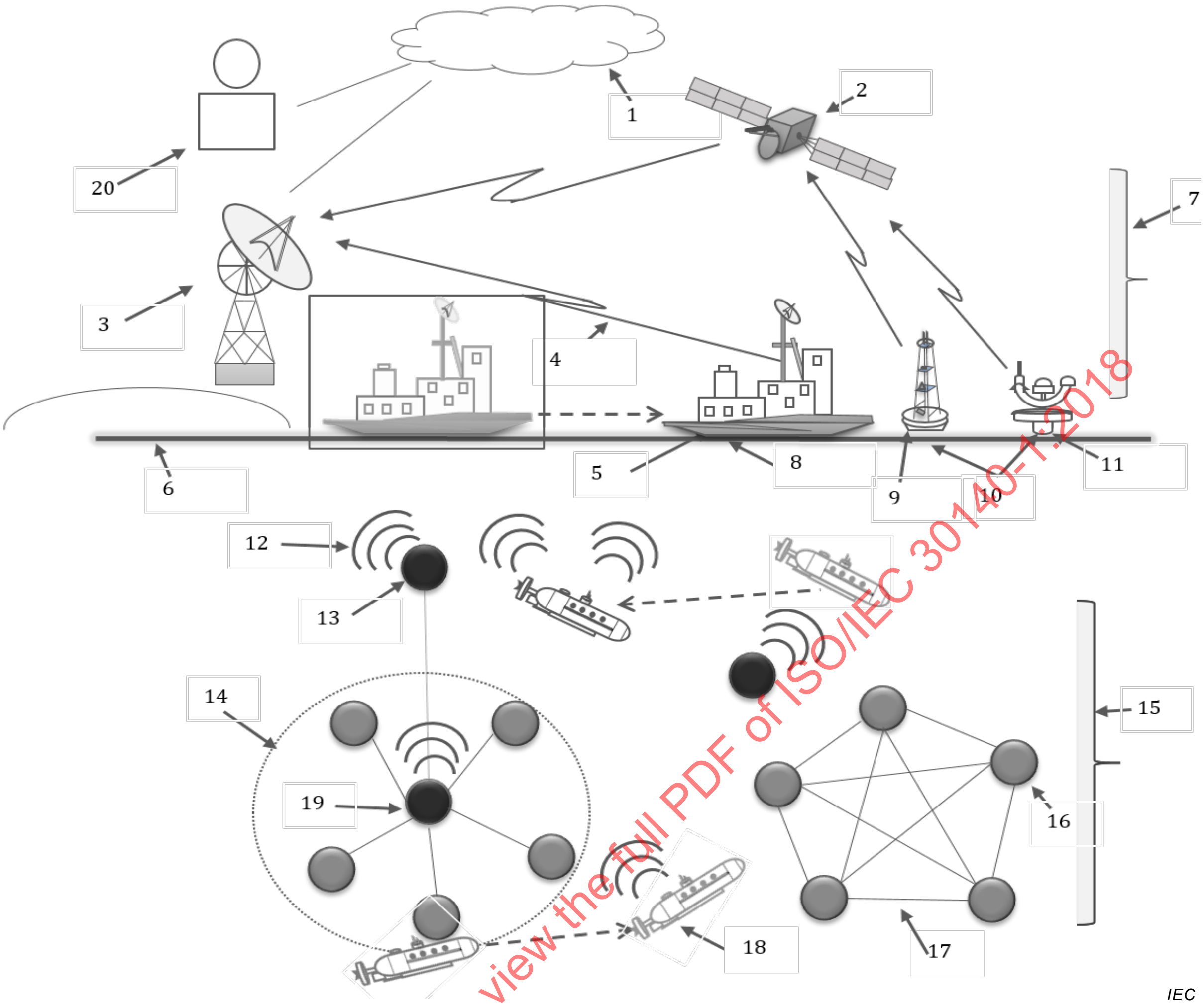
4 Abbreviated terms

2D	two dimensional
3D	three dimensional
BER	bit error rate
DG	distance group
DTN	delay and disruption tolerant network
EM	electromagnetic wave
EMI	electromagnetic interference
GPS	global positioning system
kbps	kilobits per second
LED	light emitting diode
μPa	Micropascal
Mbps	megabits per second
MCCP	minimum cost clustering protocol
QoS	quality of service
RF	radio frequency
RSS	received signal strength
UUV	unmanned underwater vehicle
UWASN	underwater acoustic sensor network
UWA-CH	underwater acoustic cluster head
UWA-DTN	underwater delay tolerant network
UWA-DTN-GW	underwater DTN gateway
UWA-EUN	underwater acoustic extend united network
UWA-FN	underwater acoustic fundamental network
UWA-GW	underwater acoustic gateway
UWA-SNode	underwater acoustic sensor node
UWA-UN	underwater acoustic united network

5 UWASN overview and applications

5.1 Overview

Figure 1 shows the basic topology of UWASN. In a cluster-based network, the data sensed by underwater acoustic sensor nodes (UWA-SNodes) are transmitted via acoustic communication to an underwater acoustic gateway (UWA-GW) using an underwater acoustic cluster head (UWA-CH), unmanned underwater vehicle (UUV), or relay nodes. Users receive the transmitted data through various externally connected networks (e.g. radio frequency (RF) or satellite communication). During these processes, underwater communication is implemented by acoustic communication. In general, UWA-GWs are either moving nodes or fixed nodes. Topologies and communication configuration models could be adaptively modified according to the application domain's needs at any given time.



Key

1	Internet	6	Surface	11	UWA-DTN-GW	16	UWA-SNode
2	Satellite	7	RF	12	Acoustic link	17	Ad-hoc network
3	Base station	8	UWA-GW	13	Relay node	18	UUV
4	RF link	9	Buoy	14	Cluster	19	UWA-CH
5	Moving gateway	10	Fixed gateways	15	Underwater	20	User

Figure 1 – Overview of a UWASN

RF communication systems are used in terrestrial sensor networks. The reasons for this are their high efficiency and low cost. Underwater RF communication is very difficult due to limited wave propagation characteristics that arise from the high attenuation due to the conductivity of water. Underwater communications can also be achieved by optical links employing lasers or LED light sources. Optical waves are still affected by attenuation, but can typically operate over longer ranges than RF.

Diode laser beams and low cost light sources such as LEDs can also be utilized. A light source for an underwater communications system is practicable using LEDs with an optical wavelength between 400 nm and 550 nm.[3]

Presently, underwater acoustic communication is the primary method for establishing wireless communication among UWA-SNodes, UUVs and UWA-GWs. This is because sound travels much further in water than RF radio signals. A UWASN consists of different types of

UWA-SNodes and UUVs positioned so as to perform collective underwater monitoring. UWA-SNodes and UUVs are organized autonomously into a network that should adapt to changing ocean environments over time.[4]

UWA-SNodes are applicable to pollution monitoring, oceanographic information gathering, strategic observation, assisted navigation, offshore examination, and disaster prevention. Several UUVs with equipped sensors explore underwater resources and gather precise location information. To make this possible, reliable underwater communication between UWA-SNodes and UUVs is required.

UWA-SNodes and UUVs should have self-configuration capabilities that allow them to network themselves. They should manage the operations by sharing location information, configurations, and movements, in order to send monitored data to an on-shore location.

5.2 Application domain of UWASN

A UWASN can realize unexplored underwater applications, increasing the capacity for detecting and forecasting changes in time-varying oceanic environments. Table 1 shows the UWASN market segments and their current and future potential applications.

Annex A provides a description of the selected application of UWASN.

Table 1 – UWASN market segments and their current and future applications list

Market segment	Description
Scientific applications	Early warning system for detection of disasters and tsunami, and providing warnings Studying the effects of oceanic earthquakes (seaquakes) Climate recording Pollution control Oil/gas fields exploration Detecting climate change Improving weather forecasting Studying marine biology Ocean circulation studies
Business applications	Discovery of natural resources Temperature monitoring in runtime Chemical and biological changes Detection of pipeline leakages Seismic monitoring allowing reservoir management approaches
Civilian applications	Assisted navigation Identifying hazards in the seabed Identifying submerged wrecks Identify the mooring positions Underwater hazard avoidance Defining seabed pipeline routes Identifying underwater oilfields Defining paths for the layering of underwater cables
Aqua applications	Aquaculture and farming Remote control-monitoring of costly devices

Market segment	Description
Military applications	Strategic surveillance Monitoring port facilities Securing foreign harbours Mine countermeasures Submarine monitoring Intruder detection Ocean bottom imaging and mapping

6 Characteristics of UWASN in terms of the effects of propagation variability

6.1 Underwater acoustic communication

Underwater acoustic communication method is used for underwater data transfer. It can establish acoustic communication with the help of transducers. Due to time variations of the channel, limited bandwidth, multipath propagation, and strong signal attenuation, underwater communication is difficult. Because of the high conductivity of seawater, acoustic communication works far better than the RF communication.

Concerns that should be examined while planning UWASN system are:

– attenuation of water limits sound's propagation distance;

– path dependent, low propagation speeds of the sound, varying in the interval of (1 500 ± 120) m/s;

– echoes and interferences caused by multipath(s) due to sea bottom and sea surface reflections, as well as between the layers of water body with different densities;

– acoustic signal disturbed by different characteristics of underwater channel and Doppler's effect not only from motion of transmitter and receiver but also from time-variability of the surface and water column [5];

– noise level in underwater can corrupt or block parts of signal.

Sound is produced when an object vibrates and transmits motion to the surrounding physical medium. This results in the propagation of vibrations, where the particles in the medium oscillate in the same direction as the propagation.

6.2 Acoustic signal strength attenuation

A sound's intensity is reduced with distance through the medium in which it travels. In idealized materials, a sound's signal amplitude weakness because of wave spreading. Attenuation is another reason for weakening of sound.

a) Absorption

Converting sound energy into some other form is called absorption. Acoustic waves are converted to heat due to absorption [6].

b) Sound speed profiles

The speed of sound in water depends on several parameters such as temperature, salinity and pressure [7]. In general, sound speed in water increases with increasing water temperature, salinity and pressure.

6.3 High propagation delay

Sound's slow underwater propagation speed can be differentiated from electromagnetic propagation. Sound's underwater speed is influenced by underwater properties such as pressure, salinity, and temperature, which are openly associated with depth. The salinity of all shallow seawater associated with rivers, and some seawater with ice in the Antarctic or Arctic, can change. Near the sea surface, sound's underwater speed is more than four times faster than its speed in air.

The bending of a sound signal is caused by underwater inhomogeneity characteristics. This commonly occurs in the vertical way because of three factors: (1) water temperature changes due to the non-uniform heating by the sun's rays, (2) salt concentration changes, and (3) hydrostatic pressure changes due to depth. The sound curvature direction is influenced by the sound velocity distribution of the medium. Sound signals are bent downward in summer because the upper layers of water are warmer than lower layers. Sound signals are bent upward in winter because the temperature of lower water is retained. Therefore, the range of sound propagation is greater in winter than in summer.

6.4 Multipath

In underwater environment, the signal propagates from the transmitter to the receiver via either direct or multipath propagation. Additionally, the mechanisms of the multipath formation in the ocean depend on channel geometry, signal frequency, sound speed profile, range of transmission, and depth of water.

Owing to reflection or refraction of the acoustic waves, there would likely be underwater multipath(s) of acoustic waves. As acoustic waves bounce, either at the surface or bottom of the sea or from water turbulence, and reach the receiver, reflections of the acoustic waves occur, resulting in multipath propagation of the acoustic waves. This kind of reflection is common in shallow water. Acoustic wave refractions usually occur in deep water environment, where the speed of sound changes with depth.

Since horizontal communication takes place in underwater, multipath propagation should be considered. Water surface reflections, bottom reflections, and water turbulence reflections can generate the multipath. To reduce multipath effects, directional remote transducers can be used. However, if there are obstacles nearby, the modem will experience dynamic multi-pathing that is rapidly fluctuating due to reflections, and the performance of the modem drops dramatically. Therefore, the multipath powers a constant trade-off between a modem's cost and its reliability [8].

6.5 Propagation loss

Propagation loss is collective impact of attenuation, absorption loss, and geometric spreading. In water, sound travels more than four times quicker than in air. Sounds are transmitted as a pressure wave in water, like in open air. Sound pressure is measured in decibels (dB) with reference to one micropascal (μPa). The noise sources in UWASN channels are separated into ambient noise and man-made noise.

– Attenuation

  Attenuation is created through absorption while transforming acoustic energy to heat. It is increased by frequency and distance. At a rough ocean bottom and surface, attenuation is initiated by scattering. Attenuation is also started by refraction and is also influenced by water depth.

– Geometric spreading

  This is the spreading of sound energy by waves. It is frequency independent and increases with propagation distance. The common geometric spreading approximations are cylindrical spreading and spherical spreading.

6.6 Noise

There are two types of noise sources in UWASN channels: (1) ambient noise; and (2) man-made noise.

1) Ambient noise

   This is associated with the seismic and biological activities of water, and it is also related to water movement due to rain, wind, storms, etc.

   Ambient noise affects the received signal-to-noise ratio (SNR) and also affects the required transmitter power. UWASN should consider these situations. Ambient noise in the monitoring water body should be considered for selecting receivers due to its impact on the received SNR and for sizing transmitter power [9].

2) Man-made noise

   In water, man-made noises are produced by shipping activity and various kinds of underwater devices such as pumps. Marine worksites locations have more noise.

7 Differences between UWASN and terrestrial sensor network

7.1 Types of underwater communication technologies

The design of the underwater communication system should consider the multipath and limited bandwidth of the underwater medium. Current underwater communication systems use optical, radio or acoustic transmission. Depending on application and design requirements, these methods have advantages and limitations.

a) Acoustic waves:

   In underwater environments, because of lower attenuation compared to air, acoustic waves are used for communication. Underwater acoustic wave usage is affected by the multipath, water temperature, and ambient noise. Nevertheless, the currently favourable technique is to use acoustics for underwater communication [10].

b) Radio waves:

   Radio waves are electromagnetic waves. The underwater speed of EM waves is approximately 200 000 times faster than acoustics; for this reason, network latency is impressively compact. EM waves are not sensitive compared with acoustics for multipath effects in shallow water [11].

   RF can work underwater only for short distances; for long distance underwater communication, radio waves cannot work efficiently.

c) Optical waves:

   Free-space optical (FSO) waves in the blue-green wavelengths contain 10 Mbps to 150 Mbps of high-bandwidth communication in the 10 m to 100 m or longer range.

The important features of optical, acoustic, and radio waves for a UWASN in a seawater environment are given in Table 2 [6].

Table 2 – Summary of the features of acoustic, radio, and optical waves in seawater environments

Feature	Acoustic	Radio	Optical
Attenuation	Low	Moderate	High
Effective range	several kilometres	several metres	several metres
Propagation delay	High	Low	Low
Heavy constraints	Bandwidth-limited Interference-limited Environment-limited.	Power-limited Environment-limited.	Environment-limited

Table 3 shows the benefits and limitation of three underwater communication technologies using the three types of waves introduced in Table 2.

Table 3 – Differences between underwater communication technologies [10][12]

Technology	Benefits	Limitations
RF	High bandwidth at very close range Simply able to cross seabed, air, and water boundaries Not affected by turbidity and pressure gradients Works in non-line-of-sight, not affected by sediments and aeration	Range is limited in water Has limited wave propagation characteristics that arise from the high attenuation due to the conductivity of water
Acoustic	Range is up to some kilometres Verified technology	While transmitting by air or underwater, heavy reflections and attenuation Limited bandwidth Unfavourably affected by salinity, pressure, and ambient noise gradients Performance is poor in shallow water
Optical	Very high bandwidth	Easily transmitted by air or underwater Vulnerable to particles, turbidity, and marine fouling Requires line-of-sight Small range

Additional information to identify the differences between the underwater transmission media mentioned in Table 3 is as follows.

Low bandwidth: This is an important factor in UWASN. The multipath, noise, transmission loss, Doppler spread, and high propagation delay markedly affect underwater communication. The above issues control the variability of the underwater medium, which makes the medium bandwidth both limited, and intensely reliant on the frequency and range. Systems that are short range and operating over 10 m may require 100 kHz of bandwidth more, but lengthy range systems operating at more than 10 km may require bandwidth of a few kilohertz.

Range can be a factor in classifying underwater acoustic communication links.

Data rate: Instead of electromagnetic waves like terrestrial networks, UWASN use acoustic waves. For this reason, as compared to terrestrial networks, data rates are low in a UWASN.

7.2 Housing case

A waterproof housing case is needed for UWA-SNodes for preventing corrosion and failure (see 9.4).

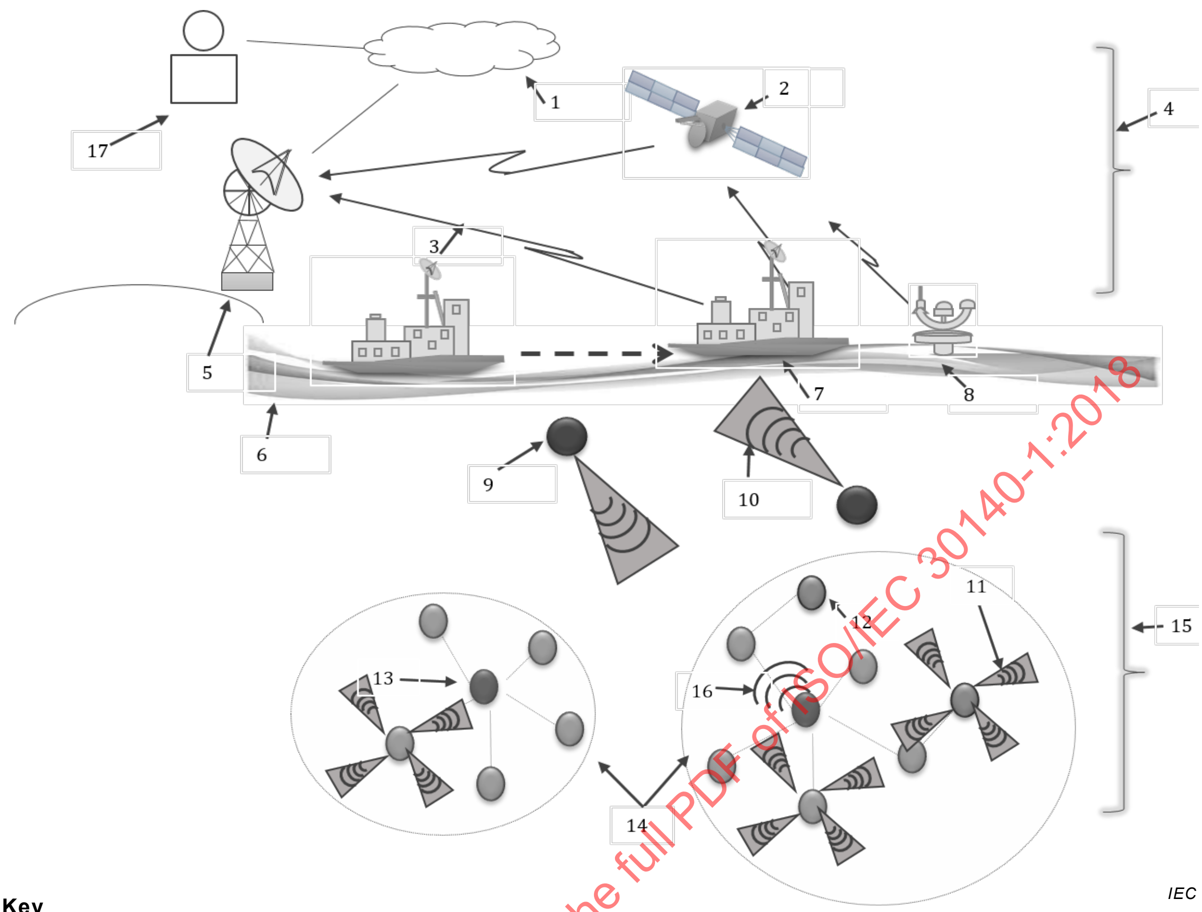
7.3 Costs associated with sensor nodes

The deployment cost of a UWA-SNode is very high compared to terrestrial sensor node and battery change is also required for reuse. Most of the UWA-SNodes except disposable nodes require nodes replacement technology, known as node reclamation [13].

7.4 Omni-directional and directional transducers for data transmission and reception

In a UWASN, omni-directional and directional transducers are needed for data between the transmitter and receiver. The underwater cluster network is a small network and uses the omni-directional transducer as shown in Figure 2.

The directional transducer has limitations in terms of mobility. This transducer radiates equally and receives equally in all directions of the cluster. Underwater relay nodes using the directional transducer by which the data is received from the UWA-CH are transmitted toward the UWA-GW. This is because the communication link between the relay node and the UWA-GWs is large. If omni-directional transducer is used, more energy would be needed and the probability of collision would be high. Therefore, instead of omni-directional transducer, a directional transducer can be used.



Key

1	Internet	6	Surface	11	Omni-directional antenna	16	Acoustic link
2	Satellite	7	UWA-GW	12	UWA-SNode	17	User
3	RF link	8	UWA-DTN-GW	13	UWA-CH		
4	RF	9	Relay node	14	Cluster		
5	Base station	10	Directional antenna	15	Underwater		

Figure 2 – Omni-directional and directional transducers for data transmission and reception

7.5 Underwater object and event localization and 3D relay node

In a UWASN, localization plays an important role in several applications and hence is an important technology. For data tagging, reporting an event occurrence or monitoring, and making routing decisions, localization is required. For example, UWA-SNodes learn the position and motion of mobile beacons; therefore, to forward data by choosing the best relay, the speed, and location of mobile beacons are used by routing protocols. Variations in the underwater acoustic channel are caused by the multipath. For this reason, localization methods suggested for terrestrial sensor networks are not suitable in underwater. Sparse deployment of underwater nodes, node mobility, and bandwidth limitations also disturb the localization estimation accuracy. Additionally, GPS signals do not penetrate the body of water due to its high RF frequency telemetry.

The following challenges are related to localization in UWASNs.

- Mobility due to in water current.
- Battery life is limited.
- Propagation of high frequency GPS signal is not good underwater.

Since a major difference is caused by the non-uniform acoustic signal propagation at the received signal strength (RSS), terrestrial localization methods that depend on RSS are not suggested for UWASNs. Many localization methods have been proposed for terrestrial sensor networks but these cannot be directly applied to underwater environments because of the individualities of UWASNs [14][15].

7.6 Energy harvesting technology for UWASN

Because it is relatively difficult to change the batteries of deployed UWASN nodes, energy harvesting is a major issue to be considered in a UWASN. The main purpose for designing an energy harvesting system is to provide a continuous and regular power supply for UWASN nodes. Underwater sensor nodes do not have direct access to solar energy, because sunlight does not effectively penetrate seawater.

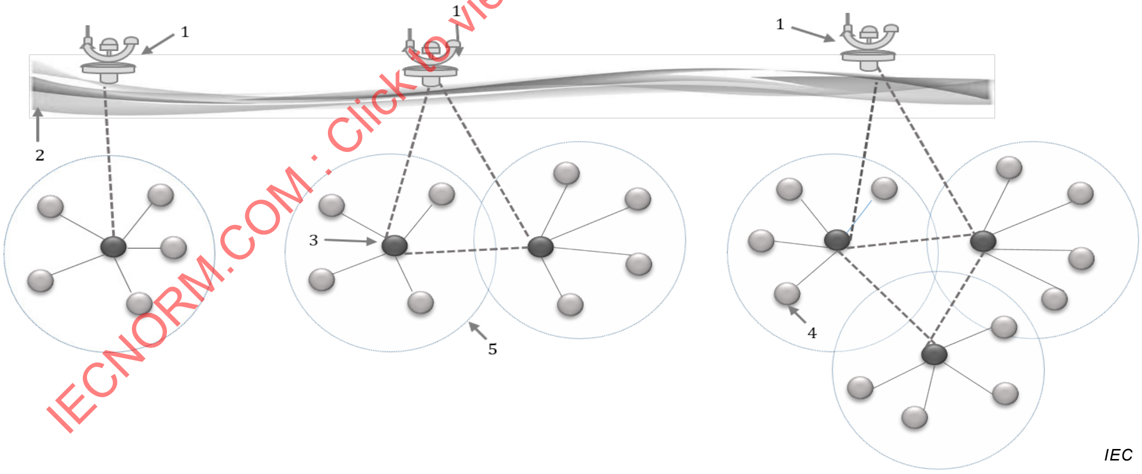
8 Specificities of UWASN and related requirements

8.1 Three structural scales of UWASN network

A UWASN has three structural network scales. The network scales are related to the network topologies.

a) Fundamental acoustic network: Underwater Acoustic Fundamental Network (UWA-FN)

The underwater acoustic fundamental network (UWA-FN) is a type of small cluster network or a small ad-hoc network. These networks use the same protocol stack, as shown in Figures 3 and 4 for a cluster network and an ad-hoc network, respectively. Every cluster contains a UWA-CH and UWA-SNodes. The UWA-CH gathers the data from its clustered UWA-SNodes and transmits data to the UWA-GW through an acoustic communication channel. In the ad-hoc network, the UWA-SNodes are either fixed or mobile nodes, and they should communicate with the UWA-GW directly or through relay nodes.



Key

1 UWA-DTN-GW

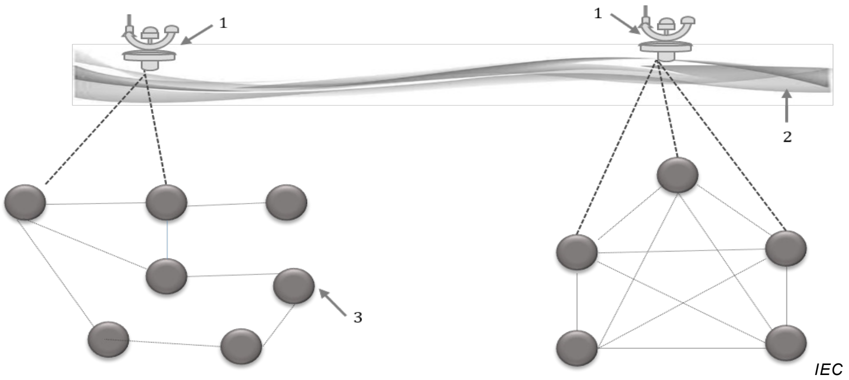
2 Surface

3 UWA-CH

4 UWA-SNode

5 Cluster

Figure 3 – Underwater cluster network



Key

1 UWA-DTN-GW

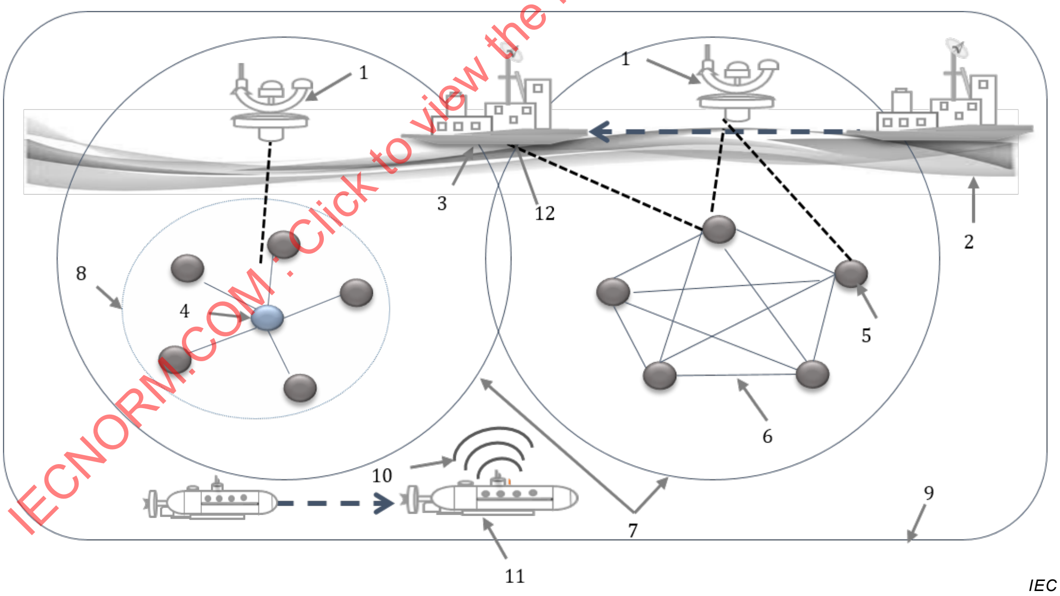
2 Surface

3 UWA-SNode

Figure 4 – Underwater ad-hoc network

b) United acoustic network: Underwater Acoustic United Network (UWA-UN)

An underwater acoustic united network (UWA-UN) consists of UWA-SNodes, UWA-CHs, relay nodes, and moving or fixed UWA-GWs, as shown in Figure 5. In deep water communication, the UWA-GW and the UWA-CH are likely separated by relatively long distances. In this case, underwater relay nodes are used to save energy and reduce the collision probability. Examples of relay nodes are UUVs. Examples of UWA-GWs are buoys and ships.

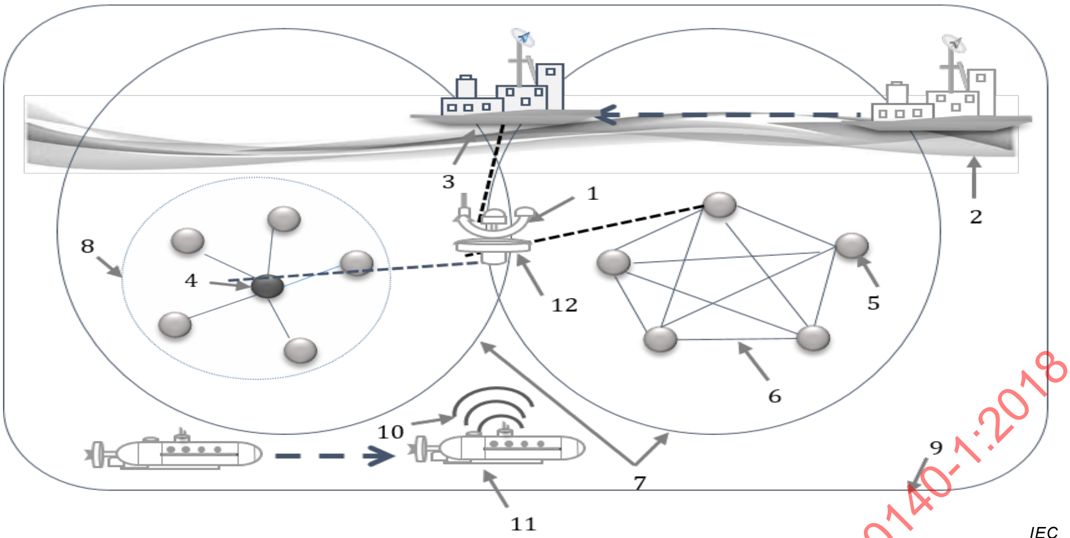


Key

1	UWA-DTN-GW	6	Adhoc	11	UUV
2	Surface	7	UWA-FN	12	Moving gateway
3	UWA-GW	8	Cluster		
4	UWA-CH	9	UWA-UN		
5	UWA-SNode	10	Acoustic link		

Figure 5 – UWA-UN communication network

Figure 6 shows the UWA-UN communication network using a fixed gateway for communication between two different types of networks: cluster and ad-hoc networks.



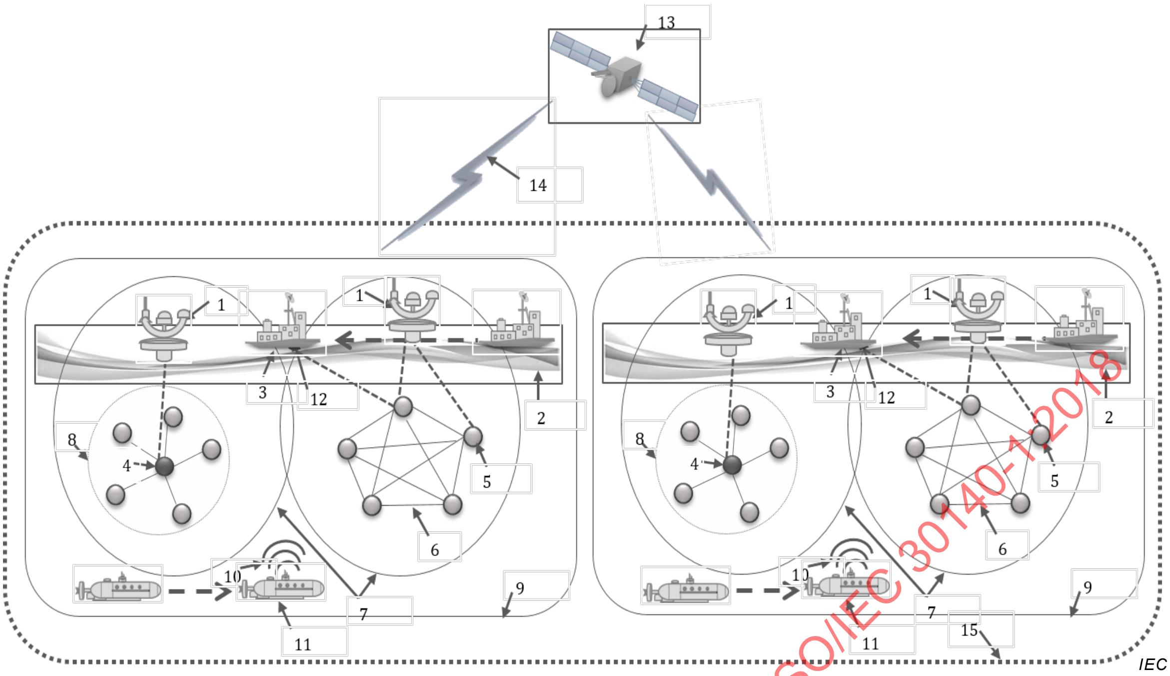
Key

1	UWA-DTN-GW	6	Ad-hoc network	11	UUV
2	Surface	7	UWA-FN	12	Fixed gateway
3	UWA-GW	8	Cluster		
4	UWA-CH	9	UWA-UN		
5	UWA-SNode	10	Acoustic link		

Figure 6 – UWA-UN communication network using fixed gateway

c) Extend acoustic united network: Acoustic Underwater Extended United Network (UWA-EUN)

The structural size of an acoustic underwater extended united network (UWA-EUN) is larger than that of a UWA-UN, and the structural size of UWA-UN is larger than that of a UWA-FN (i.e. UWA-EUN ⊃ UWA-UN ⊃ UWA-FN). UWA-EUN can include UWA-FNs and UWA-UNs. UWA-GWs communicate with the terrestrial network through satellite communication. Figure 7 shows the structure of UWA-EUN.



Key

1	UWA-DTN-GW	6	Ad-hoc network	11	UUV
2	Surface	7	UWA-FN	12	Moving gateway
3	UWA-GW	8	Cluster	13	Satellite
4	UWA-CH	9	UWA-UN	14	RF link
5	UWA-SNode	10	Acoustic link	15	UWA-EUN

Figure 7 – UWA-EUN communication network

8.2 Deployments of 2D and 3D topology

8.2.1 General

Two communication architectures are used to deploy UWA-SNodes: 2D and 3D architectures.

8.2.2 Two-dimensional UWASN architecture

The reference architecture for 2D UWASN is shown in Figure 8. With deep ocean anchors, groups of UWA-SNodes are anchored to the sea bottom. UWA-SNodes are associated with the UWA-CH with the help of acoustic links. UWA-CHs use vertical and horizontal links.

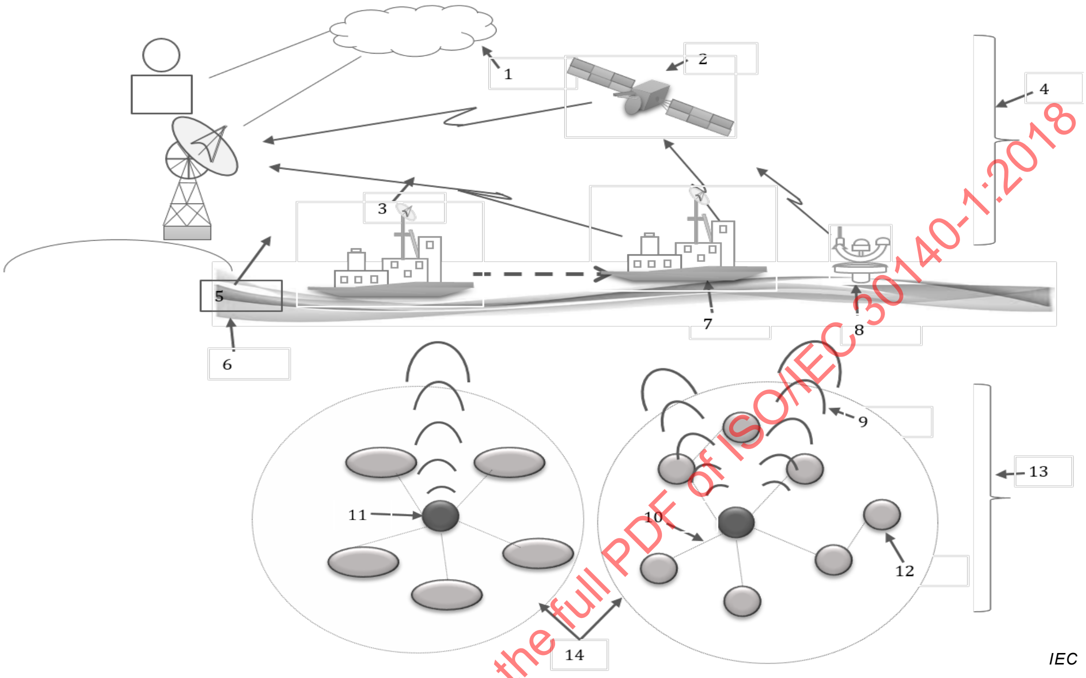
The UWA-CH uses horizontal links to communicate with the UWA-SNode in order to achieve the following:

– send configuration data to UWA-SNodes and give commands; and
– gather monitored data from UWA-SNodes.

The UWA-CH also uses vertical links to send data to UWA-GW. As the sea can be 10 km deep, vertical links should use long range transceivers in deep water applications. With the deployed UWA-CH, the UWA-GW is equipped with an acoustic transceiver to handle multiple parallel communications. UWA-SNnodes can be connected to UWA-CHs via multi-hop paths or direct links.

Challenges associated with a 2D UWASN [16] are as follows.

– Application requirements dictates the determination of minimum number of UWA-SNodes and UWA-GWs that are required to be installed to accomplish communication coverage and target sensing.
– Target bottom coverage area gives the selection criteria to choose optimal deployment region; and estimation of number of redundant UWA-SNodes to be installed to compensate for the node failures.



Key

1	Internet	6	Surface	11	UWA-CH
2	Satellite	7	UWA-GW	12	UWA-SNode
3	RF link	8	UWA-DTN-GW	13	Underwater
4	RF	9	Vertical link	14	Cluster
5	Base station	10	Horizontal multi-hop link		

Figure 8 – Two-dimensional UWASN architecture

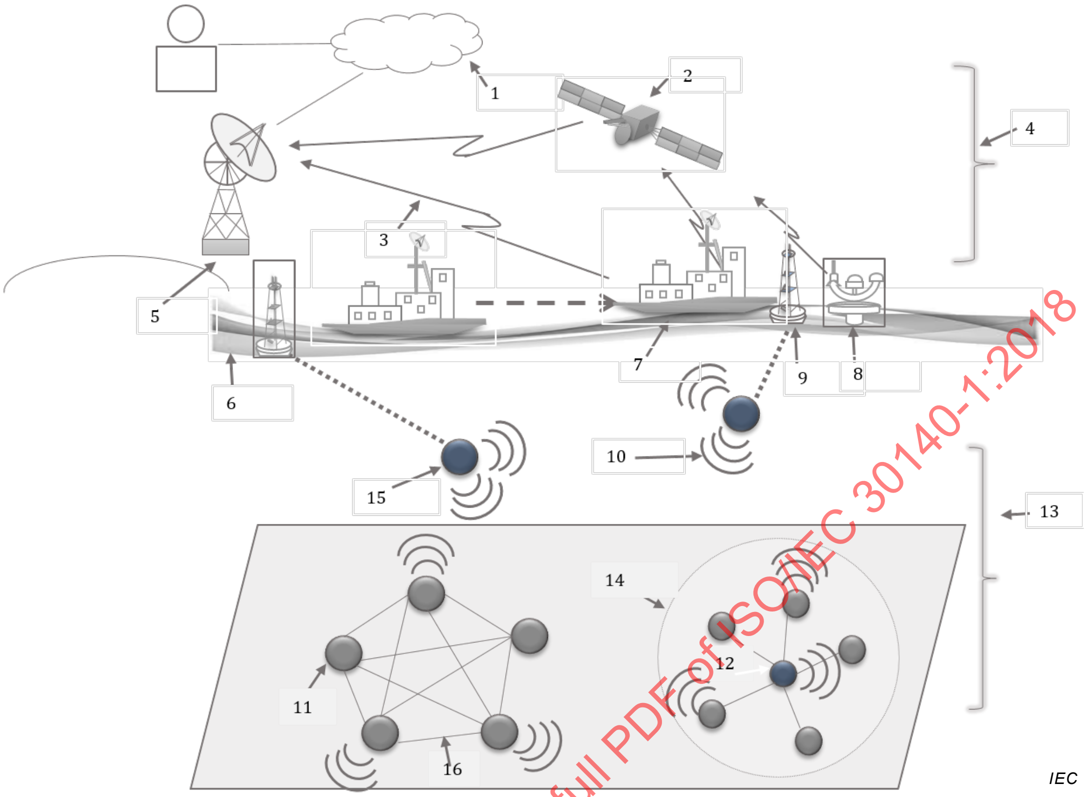
8.2.3 Three-dimensional UWASN architecture

The 3D reference architecture of the underwater acoustic sensor network is given in Figure 9. To observe the required monitoring area in 3D UWASN, UWA-SNodes float at different depths. This can be achieved by attaching each UWA-SNode to a surface buoy using wires. This setup has two disadvantages: (1) ships may be obstructed by the buoys; and (2) UWA-SNodes may be detected and deactivated by enemies. Floating buoys may be exposed to climate, theft, and tampering. Because of above mentioned reasons, different approach should be taken into account for anchoring UWA-SNodes [17].

Challenges associated with 3D UWASN are as follows.

– Sensing coverage: Based on sensing range UWA-SNodes should collaboratively adjust their depth. This adjustment helps to achieve 3D coverage of an ocean column. At all depths, it should be possible to perform sampling of the anticipated phenomenon.
– Communication coverage: Through multi-hop links, UWA-SNodes relay data to the surface station. Network devices manage their depths so that the network topology stays

connected. This means that one path should exist between the UWA-SNode and the UWA-GW.



Key

1	Internet	6	Surface	11	UWA-SNode	16	Ad-hoc network
2	Satellite	7	UWA-GW	12	UWA-CH		
3	RF link	8	UWA-DTN-GW	13	Underwater		
4	RF	9	Buoy	14	Cluster		
5	Base station	10	Acoustic link	15	Relay node		

Figure 9 – Three-dimensional UWASN architecture

In the 2D and 3D underwater acoustic sensor network architectures, UWA-SNs are normally powered by batteries. However, there are disadvantages to battery use in UWA-SNs as follows.

a) Replacing depleted batteries costly and time-consuming, especially when the number of UWA-SNs is increased.

b) A UWA-SN battery has limited energy.

c) As the battery's chemical composition includes toxic heavy metals, batteries have disposal issues.

After UWA-SNodes are deployed, the network topology should be in a static state and the network can exist in 2D or 3D at the surface or on the sea floor. For 2D, the topology of the network might be cluster, line-relay, grid, or tree deployment. For 3D, UWA-SNodes could be moored to floats at fixed depths or to anchors on the ocean floor. In 3D underwater acoustic sensor network architecture, sea floor anchors are used to sparsely deploy underwater sensor nodes. As depth increases, the effect on sound speed is controlled by water pressure.

Table 4 provides the comparison between two architectures.

Table 4 – Comparison between 2D and 3D UWASNs.

Parameter	2D-UWASN	3D-UWASN
Coverage requirement	Two-dimensional sensing coverage	Three-dimensional sensing coverage
Monitoring	Ocean bottom	Ocean column
Architecture	Cluster-based	Ad-hoc based
Design	Simple	Complex
Power	Low	High
Node mobility	Fixed / Mobile	Fixed / Mobile
Localization techniques	Not needed	Needed
Communication path	Direct / One-hop path	Multi-hop path
Communication coverage	Limited region	Entire region

8.3 Cross layering

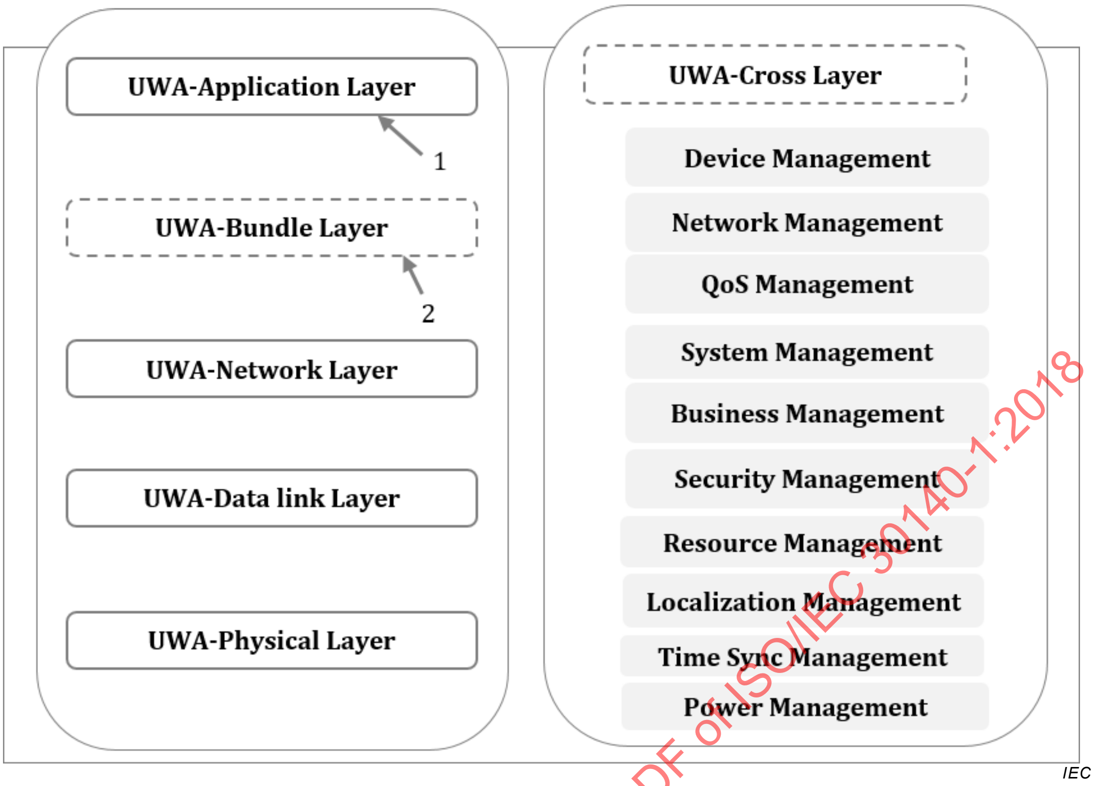
A protocol stack for a UWASN should support cooperation between UWA-SNodes. It also combines power awareness and management in the protocol. The protocol should contain functionalities of the physical, datalink, network, bundle, and application layers.

Stack of protocols should consist of device management, network management, QoS management, system management, business management, security management, resource management, localization management, time synchronization management, and power management. See Figure 10.

For certain applications, minimizing the energy consumption with the help of sleep modes and power control, etc., at the nodes should be the responsibility of power management.

Depending on applications, the precision of time synchronization of the clocks in the underwater sensors is imperative for management related to data aggregation, sleep modes, 3D topology optimization, etc.; thus, time synchronization should be maintained for all involved nodes in the networks.

Localization management is important because the relative or absolute localization information is provided to the UWA-SNode, once it is required for protocol stack.



Key

1 Mandatory

2 Optional

Figure 10 – UWA-cross layer protocol stack

8.4 Underwater acoustic modem

Underwater acoustic modems are used to transmit and receive underwater data. The purpose of the acoustic modem is to convert digital data to acoustic signals. A receiver acoustic modem converts the acoustic signal to digital data. As compared to telephone or cable modems on land, the data rate of these modems is very slow.

8.5 Doppler spread

Two kinds of effect are associated with the Doppler spreading: (1) a simple frequency conversion, which can be relatively easily compensated for by the receiver; and (2) continuous spreading of the frequencies which leads to a Doppler spread signal that is not easily compensated for by the receiver [18].

The following points explain the reasons for considering Doppler spread in underwater environment.

a) The frequency spreading that leads to Doppler spread can be substantial in underwater channels, causing degradation of digital communication performance. In an underwater communication channel, a high data transmission rate could be a reason for interference between several adjacent symbols near the receiver.

b) Doppler spread yields modest frequency translation for a receiver, which is reasonably easy to address, whereas addressing constant frequency scattering, which establishes a non-shifted signal, is problematic.

Therefore, a receiving signal should be compensated or minimized as much as possible using an algorithm or algorithms at the receiver or downstream processing.

8.6 Deployment considering water depths

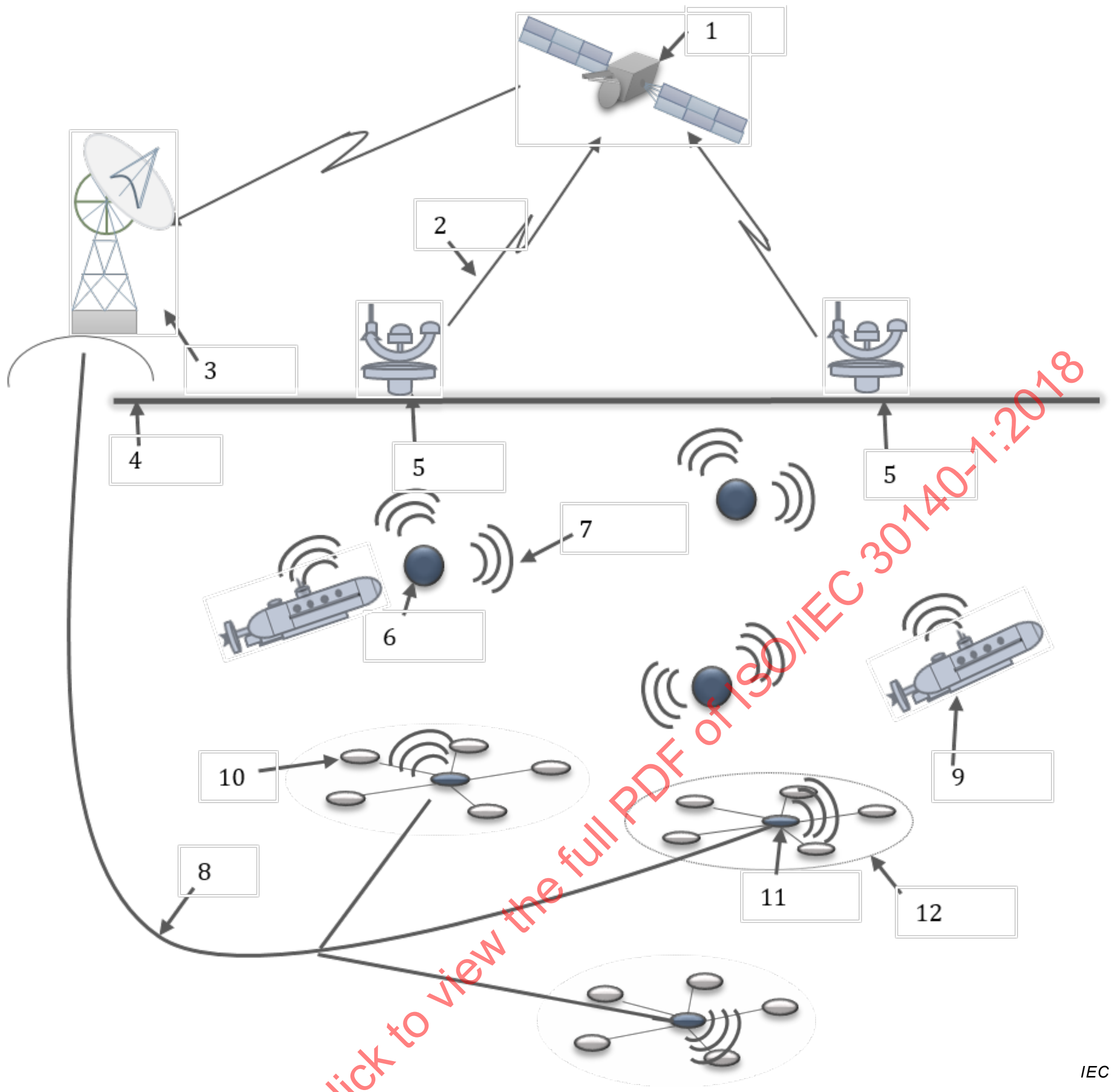
UWA-SNodes deployment can be deterministic, i.e. UWA-SNodes are positioned manually and data is transmitted over pre-determined paths. One of the fundamental tasks for UWASNs is node deployment where numerous essential network services are supported by deployment strategies, such as boundary detection, routing, and network topology control. Because of the distinctive features of underwater channels and complex deployment environments in 3D space, various issues must be considered at the time of UWASN deployment. Deployment quality and cost are two conflicting aspects [16].

The properties of the medium through which a sound wave travels have a significant impact on UWASN. In this case, network performance differs markedly depending on water depth, water type, and climate. To overcome the performance irregularities, some systems for underwater communications are designed and configured for consistency even when functioning in severe conditions. Even when reasonable propagation surroundings exist, such network configurations lead to sub-optimal performance. To predict which environmental features have the greatest influence is part of the challenge in optimizing performance. Therefore, it is necessary to estimate water pressure before the deployment of underwater nodes.

8.7 Underwater wired and wireless communication

Acoustic communication has long been used to wirelessly transmit data underwater. From a transducer, electrical energy is amplified and transmitted in water as acoustical energy. The process is displayed in Figure 11.

Each UWA-SNode is in a sleep state for some time before waking up to communicate. When sleeping, the UWA-SNode turns off the transceiver, and sets a wake-up timer. Based on the application scenario, sleeping and listening times can be selected. In some emergency applications, each node stays powered at all times during operation, to provide immediate communications in an emergency situation.



Key

1	Satellite	6	Relay node	11	UWA-CH
2	RF link	7	Wireless acoustic link	12	Cluster
3	Base station	8	Wired communication		
4	Surface	9	UUV		
5	UWA-DTN-GW	10	UWA-SNode		

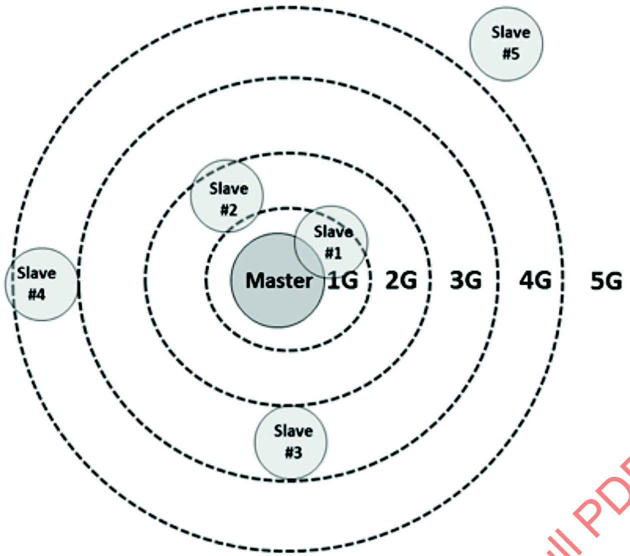
Figure 11 – Underwater wired and wireless communication

8.8 Time synchronization

Synchronizing clock time is critically significant in UWASN in order to deliver basic functionalities like power management, communication, and security. Each UWA-SNode is dispersed, and maintains its own clock (i.e. a local clock) to timestamp its time sensitive data. These time sensitive data generated by different UWA-SNodes are combined to produce a significant dataset. In a network it is essential to have a common time among all UWA-SNodes.

Because of potentially long propagation delays in underwater acoustic communications. the network performance is greatly affected by the time synchronization and scheduling for communication between UWA-SNodes in the underwater environment.

Figure 12 shows an example technique for grouping UWA-SNodes according to their distance from a master node (UWA-CH) and calculating the scheduling time. The number of distance groups (DGs) and master-slave mutual distances is based on network size and the number of UWA-SNodes, and a group according to the distance between the master (UWA-CH) and slave (UWA-SN) is produced. In Figure 12, five DGs are produced depending on the number of UWA-SNodes and the network size. A master node (UWA-CH) collects information from its slave UWA-SNodes based on the communication schedule, e.g. wake-up and sleep scheduling.



Distance Group List

Node ID	Group ID
Slave #1	1G
Slave #2	2G
Slave #3	3G
Slave #4	4G
Slave #5	5G

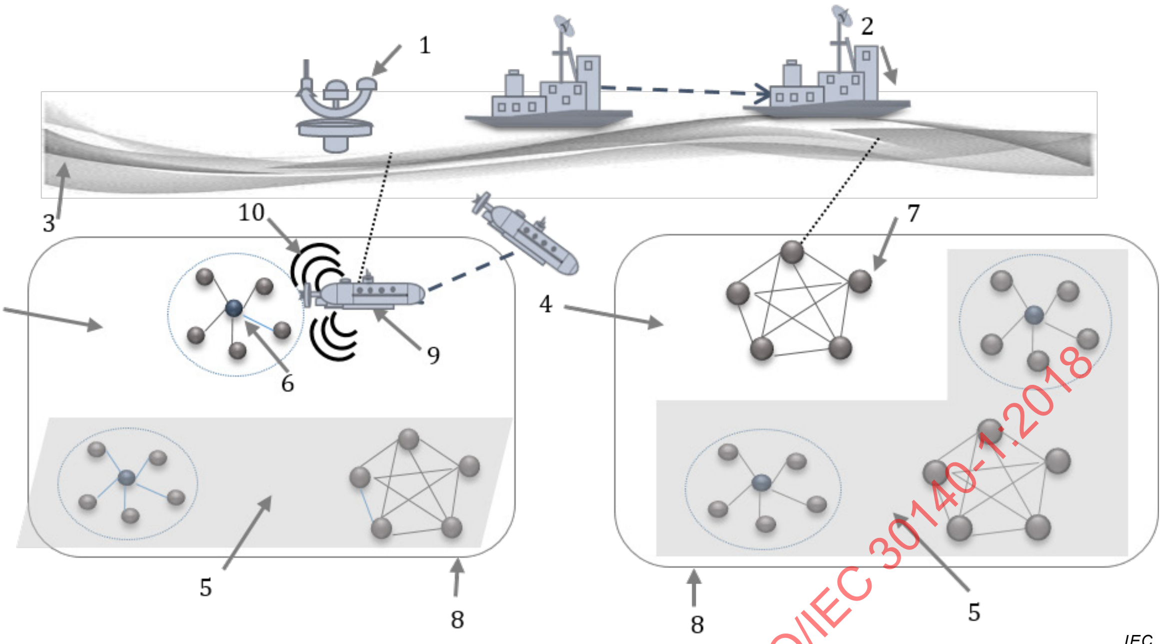
IEC

Figure 12 – Time synchronization for data transmission

8.9 Data transmission period for energy saving

In underwater communication, energy saving is optional. The UWA-SNodes communicate during their assigned time period and are otherwise maintained in sleep mode to save energy.

Active and sleep modes for energy saving: In cluster based networks, the UWA-CH controls the UWA-SNodes. However, the clusters do not need to be permanently "on" in an underwater environment. Keeping the UWA-SNodes in the active mode is wasteful of energy hence UWA-SNodes can be maintained in sleep mode when not active. Whenever an event takes place, the UWA-CH sends a wake-up call to the UWA-SNodes. After completing the required task, the UWA-SNodes again go into the sleep mode. During the sleep mode, a UWA-SNode turns off and sets a timer to wake itself alternatively, or it will awake if it receives a wake-up call from the UWA-CH.



Key

1	UWA-DTN-GW	6	UWA-CH
2	UWA-GW	7	UWA-SNode
3	Surface	8	UWA-UN
4	Active mode	9	UUV
5	Sleep mode	10	Acoustic link

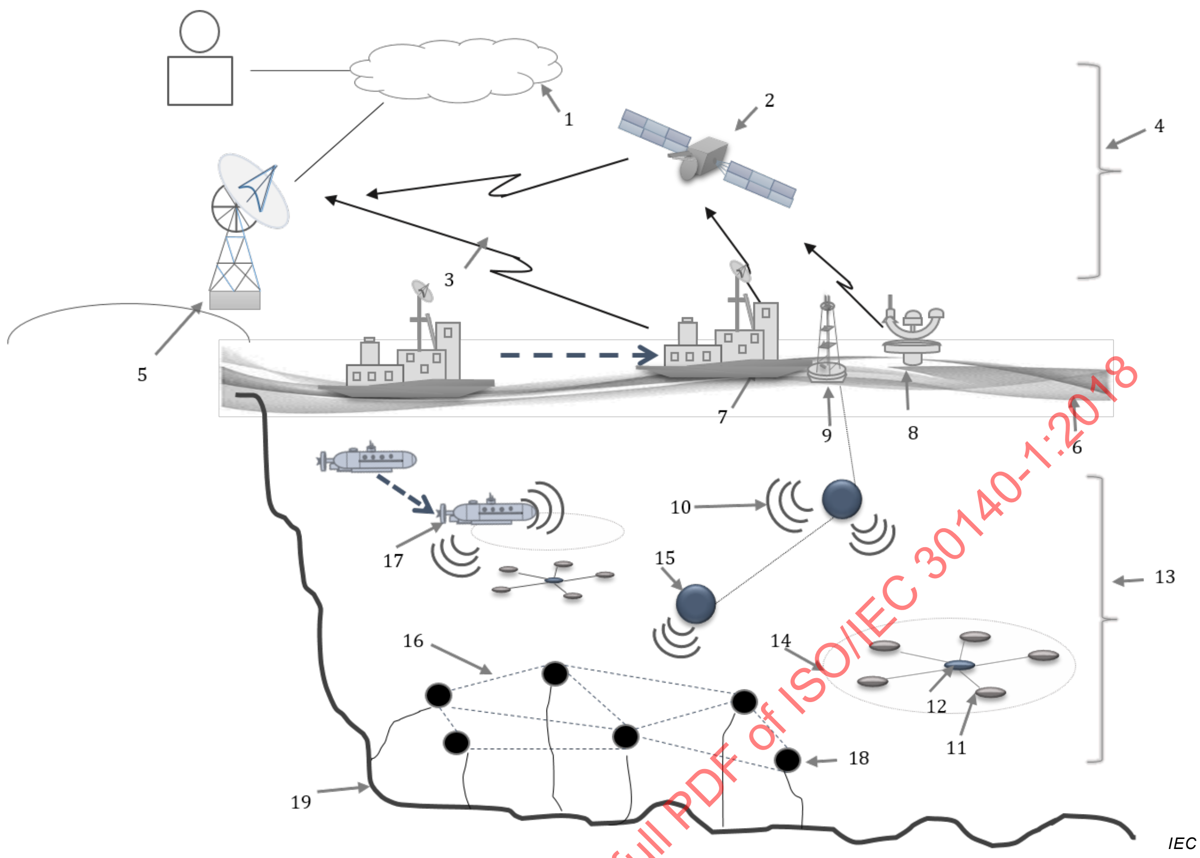
Figure 13 – Using active and sleep modes for energy saving

Figure 13 shows the UWASN architecture. Here the entire UWASN is separated into numerous networks. These networks are the cluster and ad-hoc based networks. When a moving gateway enters the communication range, only the nearest network communicates to the gateway in active mode; the remaining networks are maintained in sleep mode for energy saving.

In underwater communication, each communication layer can save energy by, for example: (1) assigning the data transmission period for communication in the application layer; (2) assigning the sleep and active modes between UWA-SNodes and the UWA-CHs in network layer; and (3) assigning communication time slots / time period between UWA-SNodes in the data link layer. Other than the assigned time slot / period, the network devices remain in sleep mode for energy saving.

8.10 Routing

Underwater environment routing differs from terrestrial wireless/surface-based routing. There are numerous challenges involved in accomplishing it. Due to the very dense, salty water in the ocean, transmission of optical and electromagnetic signals over long distances is not possible because of the acoustic signal becoming scattered, heavily attenuated, and absorbed. The UWASN routing protocols which require high bandwidth result in huge end-to-end delays.



Key

1	Internet	6	Surface	11	UWA-SNode	16	Ad-hoc network
2	Satellite	7	UWA-GW	12	UWA-CH	17	UUV
3	RF link	8	UWA-DTN-GW	13	Underwater	18	Fixed UWA-SN
4	RF	9	Buoy	14	Cluster	19	Sea bed
5	Base station	10	Acoustic link	15	Relay node		

Figure 14 – UWASN routing

The main routing protocols available to UWASN are provided here as examples.

a) Cluster based routing protocols: The protocols that utilize clustering for routing in a UWASN are discussed below.

– Minimum cost clustering protocol (MCCP): MCCP is a cluster-based protocol in which the formation of clusters takes place according to cost. Three parameters are used to compute the cost of a cluster: (1) the energy requirement for UWA-SNodes to reach to the UWA-CH; (2) the relative positions of the UWA-CH and UWA-GW; and (3) the residual energy of the UWA-CH and UWA-SNodes.

– Distributed underwater clustering scheme (DUCS): This acts as an adaptive self-organizing protocol, and UWA-SNode groups having a UWA-CH are formed from the network. All UWA-SNodes transmit a data packet to a UWA-CH. These UWA-CHs process the signals and transmit it to a UWA-GW.

– Hydraulic pressure based any cast routing (Hydro cast): This protocol uses depth information of the UWA-SNodes along with their clustering. It is considered that no hidden UWA-SNode is contained within selected clusters during the cluster formation process.

b) Ad-hoc based routing protocols: For routing, protocols like dynamic source routing (DSR) ad-hoc on-demand distance vector (AODV), destination sequenced distance vector (DSDV), gossiping under water MANET (GUWMANET), SEAWEB, optimized link state routing (OLSR), and others utilize an ad-hoc approach in the UWASN.

8.11 Network coding

The main property of an underwater acoustic channel is packet loss. Acoustic channels could be major barriers to the effective transmission of underwater data. UWASNs suffer from long propagation delays and the low value of the link quality indicator requires efficient and intelligent approaches to error recovery. In this regard, network coding has been suggested as one of the best techniques, with high assurances in terms of error recovery and improving network throughput.

In network coding, several incoming packets can be coded by a node to a single (or more) outgoing. With this, in addition to forwarding, nodes can process the incoming information flows. When independently originated and consumed data streams are transported in the network, they do not necessarily need to be kept separate. Methods exist to extract independent information after they are combined. The network coding allows for benefits, such as resilience to link failures, wireless resources, complexity, security, and throughput, in different areas of the communication network.

8.12 Data compression

The process of reducing data size is called data compression. Data compression is advantageous because it permits devices to store or transmit the same quantity of data in fewer bits. Its significant application is important in data transmission and data storage. Compression can be performed in either a lossless or lossy manner. In the case of lossless compression, bits are reduced by identifying and eliminating statistical redundancy. There is no information loss in lossless compression. Lossy compression is performed by reducing the bits via the identification and removal of unnecessary information.

The UWA-SNodes are resource constrained because power supply, processing speed, bandwidth, and memory space are limited. By applying data compression, there is a possibility to maximize the utilization of these resources. In underwater communications, much less power is consumed by data processing than data transmission. To reduce the power consumption in a UWA-SN, data compression should be applied before transmission.

8.13 Delay and disruption tolerant network (DTN)

DTN stands as highly heterogeneous system, in which end-to-end communication does not exist due to frequent link breakages, transmission capacity and link delay change over time.

DTN network for UWASN shall support the following features for supporting heterogeneous networks that communicate via DTN.

a) Intermittent connection: The DTN network maintains the status of the connection; because it is intermittent, or partial, it is not guaranteed to achieve an end-to-end communication path.

b) High delay: The node waiting time, queuing time and transmission time is very high due to intermittent connection.

c) Limited resources: The computing, processing, and storage capability of node is weaker due to cost, volume, and power.

d) Heterogeneous interconnection: DTN is used for heterogeneous communication to transmit asynchronous messages. It introduces bundle layer, which allows communication between different network protocol stacks. UWA-DTN-GW acts as a consistent communication medium for interconnection messages.

e) Dynamic topology: DTN topology dynamically changes because of energy limitations, ecological variations, or other failures.

9 UWASN further general requirements

9.1 General

After analysing UWASN characteristics, the additional general requirements of a UWASN are derived into three categories: Cross layering (see 9.2); Communication technology (see 9.3); and Other systems requirements (see 9.4).

9.2 General requirements for UWASN – Cross layering

Cross layering: Cross layer is optional in UWASN. The cross layer of the UWASN should combine power management, device management, security management, resource management, localization management, QoS management, network management, system management and time synchronization management. Power management plane shall minimize the energy consumption; localization plane shall provide localization data; time synchronization management shall be responsible for data aggregation and 3D topology, device management, and network management, etc.

9.3 General requirements for the UWASN – Communication technology

The following requirements for UWASNs concern underwater communication.

Wired and wireless communication: Acoustic communication shall be used to transmit sound wirelessly in underwater. However, the acoustic energy is not strong enough to travel long distances underwater. The electrical energy shall be amplified and transmitted with the help of transducers. UWASN cable-based architectures shall use wired communication for fixing UWA-SNodes with the help of wired line.

Time synchronization for transmission: Time synchronization shall be optional in UWASN. It shall allow for successful communication between underwater devices on the UWASN. In a UWASN, UWA-SNodes might be sparsely deployed, so exact locations cannot be determined. Time synchronization shall be used for location estimation. Additionally, it shall allow UWA-SNodes to sleep and periodically wake-up to receive beacon messages; this technique helps to save energy.

Data transmission period for energy saving: In underwater communication, energy saving should be essential because of limited battery power. The network layer shall assign the sleep and active modes between the UWA-SNode and UWA-CH. The data link layer shall assign the time slots between the underwater devices. These devices shall communicate within assigned time slots and, for the remaining time, they can enter the sleep mode to save energy.

Routing: The main issue relevant to underwater routing is high density salty underwater. UWASN routing protocols that require high bandwidth result in large end-to-end delays.

Network coding: Network coding is a technique in which transmitted data exist as mixed and re-mixed packets inside the network. These packets are then transmitted. Data can be unmixed at their final destination. The main characteristic of underwater communication is long propagation delay. Through network coding, the mixing and re-mixing of messages saves energy, increases throughput, and minimizes delay.

Data compression: Due to unique characteristics of UWASN, data compression shall be used to save energy.

UWA-DTN: DTN concept shall be used to reduce delays. With the help of DTN gateway, communication between heterogeneous networks can be established.

9.4 General requirements for the UWASN – Other system requirements

Other related UWASN system requirements are as follows.

Node reclamation: In underwater communication, battery change is required for reuse of the nodes. Node pickup technology, also called node replacement, shall be used, where an operator (human or UUV) should periodically reclaim low power sensor nodes and replace them with fully powered sensor nodes.

Fouling cleaner: Fouling is a significant concern in underwater UWA-SNode deployment over long periods. Fouling cleaner should be used to clean the marine wildlife, for example algae, weeds, zebra mussels, and barnacles, attached to underwater devices. It is an option used before constructing and deploying a UWA-SNode in underwater environments [13].

Housing case: For node development in underwater communications, nodes shall be waterproof and resistant to high water pressures. The level of waterproofing durability depends on the water depths. Housing case shall be used for the construction and deployment of UWA-SNode in an underwater environment.

Annex A
(informative)

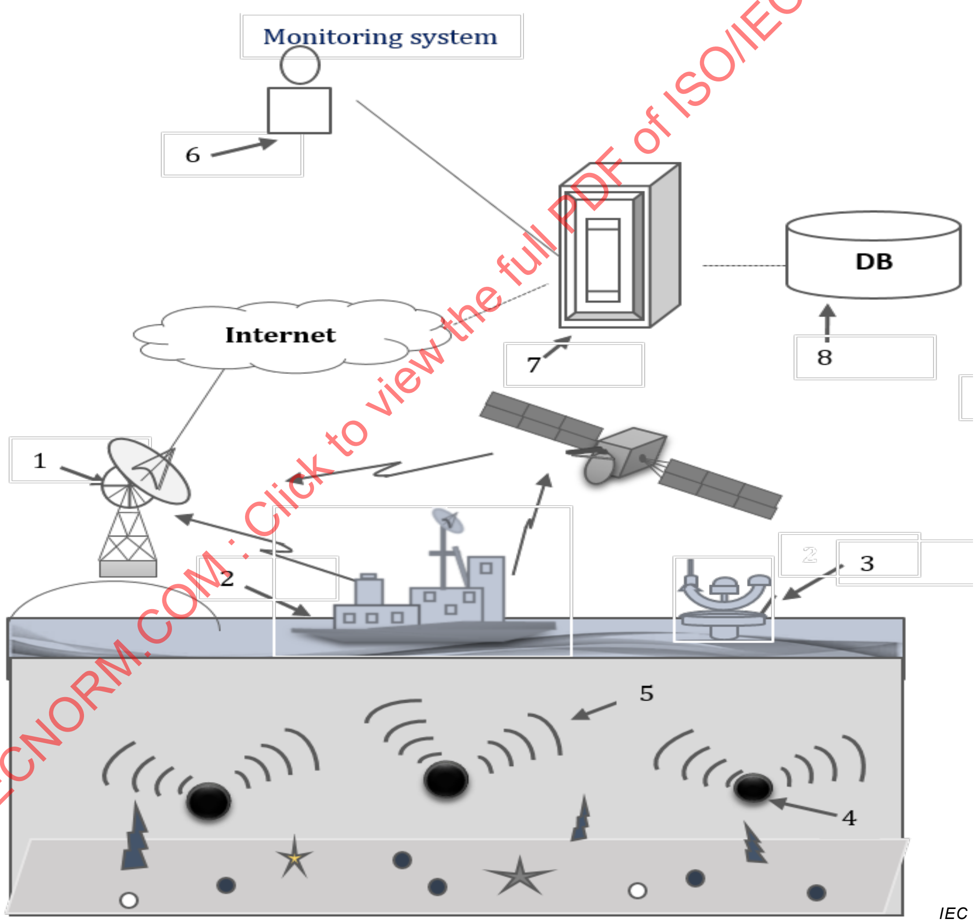
Selected applications of UWASN

A.1 Environmental monitoring – Chemical and biological changes

A.1.1 Description

In underwater UWA-SNodes are used to collect the underwater environment data such as ocean currents, salinity, temperature, pressure, and dissolved oxygen. Environmental monitoring applications include, but are not limited to, ocean currents and winds monitoring, improved weather forecast, detecting climate change, understanding and predicting the effect of human activities on marine ecosystems, biological monitoring such as tracking of fishes or micro-organisms.

See Figure A.1.



Key

1	Base station	4	UWA-SNode	7	Monitoring server
2	UWA-GW	5	Acoustic link	8	Environmental quality database
3	Buoy	6	User		

Figure A.1 – Illustration of the environmental monitoring use case

A.1.2 Physical entities

UWA-SNode – aim is to report sensing data.

User – aim is to monitor the system.

A.1.3 Normal flow

The UWA-SNodes provide sensing data to the server through the UWA-GWs.

Server stores the underwater data to the database.

Application users monitor the environment with the help of underwater data.

A.1.4 Conditions

The UWASN system needs to configure network scale for deployed nodes to properly monitor the tasked underwater environment.

Deployments of 2D and 3D topology are required based on the type of underwater environment.

Cross layering needs to be used for environmental monitoring in order to support cooperation between UWA-SNodes.

Underwater acoustic modem needs to be used to transmit and receive underwater environment data.

Data transmission frequency needs to be properly specified for energy saving in environmental monitoring.

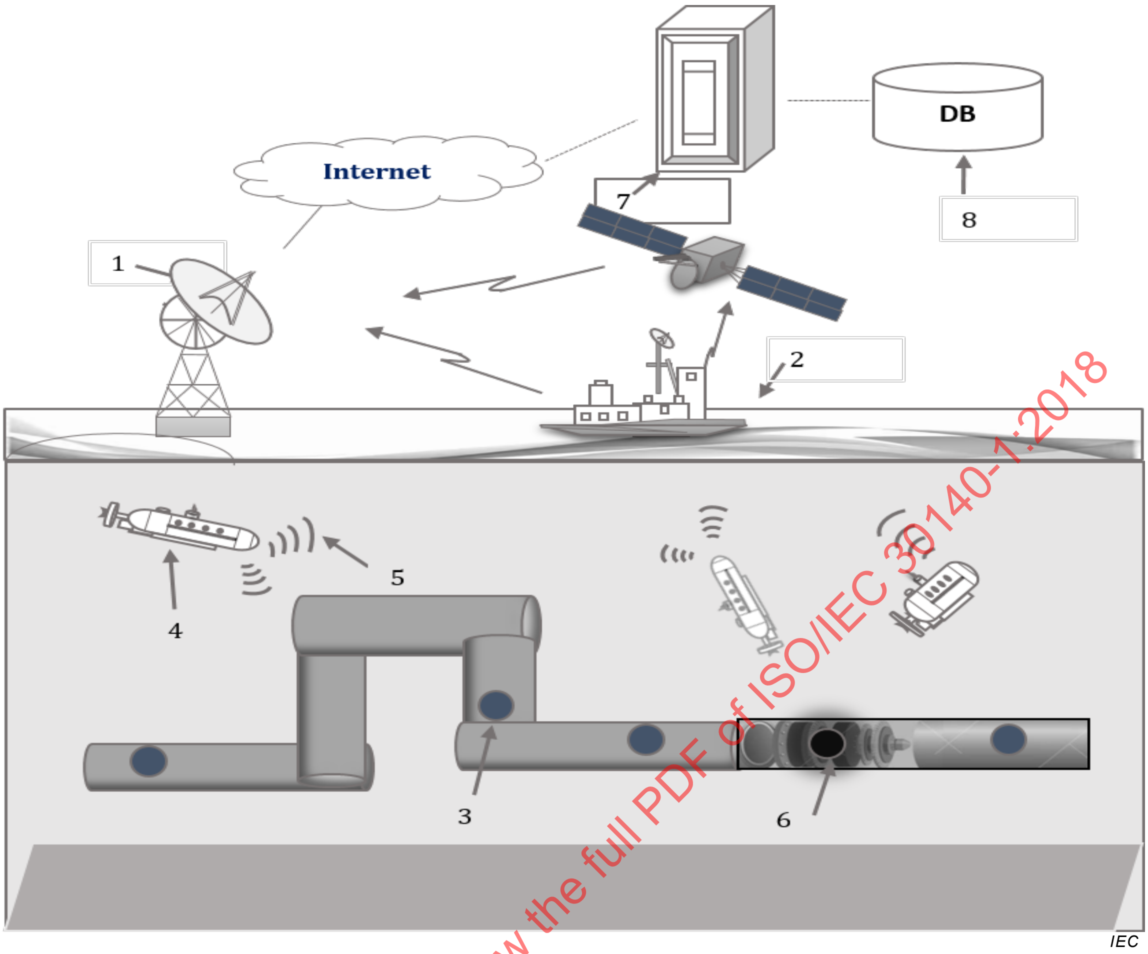
A.2 Detection of pipeline leakages

A.2.1 Description

In subsea oil and gas production fields, pipelines are an integral part of transporting the hydrocarbons to downstream processes. Problems arise in these pipelines because of corrosion, structural failure and sludge formation due to hydrocarbon chemical processes. These sorts of problems lead to production and revenue loss, as well as high maintenance costs. Furthermore, today's environmental concerns demand that hydrocarbon leaks into the ocean be avoided to prevent ecological disasters. Minimizing these problems by forecasting and timely action are of vital interest to the industry. Constant pipeline monitoring provides the data necessary to make the correct decisions.

See Figure A.2.

In pipeline monitoring, UWA-SNodes are placed along the pipeline to collect data that can be reticulated to the surface.



Key

1	Base station	4	UUV	7	Oil and gas pipeline leakages management server
2	UWA-GW	5	Acoustic link	8	Database
3	UWA-SNode	6	Broken pipe		

Figure A.2 – Oil and gas pipeline leakage monitoring use case

A.2.2 Physical entities

UWA-SNode – Aim is to report sensing data.

UWA-GW – Act as a mediator between the UWA-SNodes and UWA-GW.

Server – Constant pipeline monitoring.

A.2.3 Normal flow

See Figure A.3.

The UWA-SNodes provide sensing data to the server through the UWA-GWs.

Server stores these data in the database.

Application users monitor the pipeline leakages constantly with the help of underwater data.