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Review Article

A review on underwater acoustic sensor network

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ABSTRACT

The world's surface is covered by 71% of water in which oceans hold a share of approximately 97%. Exploration of oceans is not restricted to study of marine life or to observe the different biological changes underwater but it can also provide a great deal of information regarding climate change, natural disasters, and can provide significant data which can help us to understand the earth. This study focused on acoustic communication links as a medium of data exchange in underwater wireless sensor network. In acoustic underwater communication, the speed of sound in water is 1.5×10^3 m/s, while in air, it is about 340 m/s. The highly dynamic nature of underwater acoustic (UWA) links calls for an adaptive, scalable, and efficient routing scheme for UWA sensor networks (UASNs). Furthermore, UASN components, communication, propagation models, routing protocols, applications, and challenges have been briefly presented.

Keywords: Underwater wireless sensor network, underwater acoustic communication, propagation model, internet of things, internet of underwater things, routing protocols

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INTRODUCTION

Monitoring of underwater environment and exploring marine resources has recently increased.[1] Internet of Things (IoT) is "the network of smart interconnected underwater objects" that have the ability to connect ubiquitous devices with various networks and provide efficient and secure services for all applications.[2,3] "Underwater acoustic (UWA) sensor networks consist of a number of sensor nodes, stationary or mobile, connected wirelessly through acoustic communication modules deployed to monitor various events of interest collaboratively."[4] The concept of Internet of Underwater Things (IoUT) came up in the 2010s[5] which were driven by the unprecedented development of terrestrial IoT. IoUT is an extension of UASN for real-time tracking of underwater environments.[6] UWA sensor networks (UASNs) have been applied to underwater applications such as underwater navigation, oceanographic observation, earthquake monitoring, and oilfield exploitation.[1]

Routing in UASNs faces many issues due to the unique environmental factors of UWA.[7,8] Underwater communication makes use of low frequency and low data rate acoustic modems with a set of nodes transmitting their data to a buoyant sink nodes that relay the data to nearest control station and costal monitoring.[9] In acoustic underwater communication, the speed of sound in water is 1.5×10^3 m/s, while in air, it is just 340 m/s. It is used because of its far distance communication capability.[10] The UWA communication experiences severe loss of signals and complex multipath effect in the UWA channel[11,12] resulting in a high bit error rate in communications. There is limited bandwidth for UWA communications[13] whereas propagation delay in UWA channels is approximately five-order longer than that in terrestrial radio channels.[14,15] Due to very low speed of sound in water, communication signals suffer extreme Doppler distortions that are as a result of the transceiver motion, or the changing environments, such as internal turbulence, surface waves, and fluctuations in the sound speed. The energy requirements of UASNs are different as compared to terrestrial WSNs due to the fact that the available underwater sensors have a larger consuming power.[10] Hence, to get efficient end-to-end packet delivery over underwater acoustic links, routing protocols should have light weight signaling and the ability to adapt to the highly dynamic link quality.[1]

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UNDERWATER SENSOR NETWORKS COMPONENTS

Underwater Sensors

A typical internal architecture of an underwater sensor consists of a main controller/central processing unit which is interfaced with an oceanographic instrument or sensor through sensor interface circuitry. The electronics are usually mounted on a frame which is protected by a polyvinyl chloride housing. The controller receives data from the sensor and can store the data in the on-board memory, process them, and send them to other network devices by controlling the acoustic modem. The protecting frame may be designed so as to deflect trawling gear on impact, by housing all components beneath a low profile pyramidal frame.[16] Underwater sensor devices are equipped with a vast variety of sensors which measure the quality of water and to study its characteristics such as temperature, density, salinity, and turbidity.

Autonomous Underwater Vehicle (AUV)

In addition to sensor nodes, several types of AUVs exist as experimental platforms for underwater experiments. For example, drifters and gliders are oceanographic instruments often used in underwater exploration. Drifter underwater vehicles drift with local current and have the ability to move vertically through the water column, and are used for taking measurements at preset depths.[17] Underwater gliders (e.g., spray gliders) are battery powered AUVs that use hydraulic pumps to vary their volume by a few hundred cubic centimeters to generate the buoyancy changes that power their forward gliding.[16]

UASN COMMUNICATION ARCHITECTURE

The choice of communication architecture as shown in Figure 1 depends on the UASN applications:

1-D Architecture

1D architecture is also known as the static architecture, where the position of the nodes is static and a single network topology is followed throughout, unlike the 2D and 3D architectures.[18]

2-D Architecture

In 2D underwater wireless sensor network (UWSN) architecture, deep ocean anchors are utilized for the collection of sensor nodes and this architecture refers to a network arrangement of a cluster of sensor nodes deployed on the sea bed with an anchor node. The underwater properties gathered by the sensor nodes are sent to anchor nodes, from there, it is transmitted to the surface buoys/stations. Communication here is two phased, (i) sensed data transmission from sensor nodes to anchor node through a horizontal link and (ii) signal relay as acoustic or optical form the anchor node to the surface buoys as a vertical link and performance of the nodes is enhanced using virtual sinks.[19] 2D UW-ASN is generally preferred for their delay tolerance and time deficiency.[18]

3-D Architecture

In 3D UWSN, sensors are deployed in the form of clusters which are anchored at varying depths and heights of the seabed. The positioning of sensors determines the nature of the communication, which takes place in three tiers, namely, (i) communication between the sensors at the varying depths – intercluster communication, (ii) sensor cluster to anchor node communication – intracluster communication, and (iii) anchor node to surface buoy communication.[21] One possible solution would be to attach each UW sensor node to a surface buoy, by means of wires whose length can be regulated so as to adjust the depth of each sensor node.[22]

4-D (Hybrid) Architecture

The hybrid network architecture is a combination of fixed (3D UW-ASN) and mobile sensors such as AUVs and ROVs for signal transmission. 4D UASN an underwater mobile (ROVs and AUVs) sensor network can be used on large scale for exploration in the deep sea whereby the mobile underwater ROVs collect data from the anchor nodes and relay it to the remote.

UWA Propagation

UWA communication is a complex phenomenon due to environmental underwater factors which affect acoustic communication. The following underwater environmental factors influence acoustic communications:

Path Loss

Awan *et al*.[19] stated that sound wave propagation energy loss can be categorized into three main categories which are described below:

- Attenuation: This is mainly provoked by absorption due to the conversion of acoustic energy into heat. The attenuation increases with distance and frequency. The attenuation is also caused by scattering and reverberation (on the rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reflection point caused by wind on the surface). Water depth plays a key role in determining the attenuation.
- Geometric spreading: It is the spreading of sound energy as a result of the expansion of the wave fronts. It increases with propagation distance and is independent of frequency. There are two common kinds of geometric spreading: Spherical (omni-directional point source), which characterizes deep water communications and cylindrical (horizontal radiation only), which characterizes shallow water communications.
- Scattering loss: Deviation is a physical property regarding the line of sight of a signal or change in angle. This

property affects acoustic channel data transmission during communication. The end product of scattering surfaced is raised as surface roughness increases due to increase in the wind speed. Scattering surface affects delays as well as power loss.[4,23]

Noise

Noise can be defined as a quality of communication system that degrades signal strength of any communication system.[19] Underwater noises can be grouped into two major categories, namely:

- Human-made noise: This is mainly due to machinery (pumps, reduction gears, and power plants) and shipping activity (hull fouling, animal life on hull, and cavitation), especially in areas of heavy vessel traffic.
- Ambient noise: This is related to hydrodynamics (movement of water including tides, currents, storms, wind, and rain) and to seismic and biological phenomena. [24] stated that both noise and snapping shrimps have been found to be the primary sources of noise in shallow water by means of experimental measurement on the ocean bottom. Ambient noise is also referred as background noise which occurs as a result of unidentified sources.[23] These noises are divided into four major categories which are known as wind, shipping, thermal, and the turbulence.[25]

Multiple Paths

Multipath effect is a major cause of weak acoustic signal which result to intersymbol interference (ISI) that makes acoustic data transmission difficult and erroneous. Vertical acoustic channel is less affected by multipath effect as compared to horizontal acoustic channel.[4]

High Delay and Delay Variance

The propagation speed in the UW-A channel is five orders of magnitude lower than in the radio channel. The very high delay variance is even more harmful for efficient protocol design, as it prevents accurate estimation of the round-trip time, which is the key parameter for many common communication protocols.[26]

Doppler Spread

Doppler shift is the relative motion of transmitter and receiver that causes the mean frequency shift[19] while the fluctuation of frequency in the region of this Doppler shift is called Doppler spread.[27] The Doppler frequency spread in UWA channels causes a degradation in the performance of digital communications through transmissions at a high data rate which causes many adjacent symbols to interfere at the receiver, requiring sophisticated signal processing to deal with the generated ISI.[28]

UWA Propagation Models

UASN channel model can be splitted into three categories: [29]

Binary range-based model

It is a simple model for modeling an UASN communication environment which is achieved by deriving a binary connectivity pattern among the nodes based on a fixed connectivity range and an assumed propagation speed.[12] This model is useful for theoretical UASN protocol development but oversimplifies the behavior of the results of real time UASN channels.[29]

Urick propagation model

Urick propagation model describes propagation loss for UWA communications.

The acoustic channel is characterized by the Urick path loss formula which is as follows: [30]

$$TL(d,f)=\chi.\log(d)+\alpha(f).d+A \quad (1)$$

Where,

TL(d, f)= Transmission loss measured in dB as a function of internode distance d and operating frequency f.

χ =Geometric spreading, which can be spherical for deep water and cylindrical for shallow water.

A=Transmission anomaly

The above underwater propagation equation has three components, namely; distance-dependent attenuation, frequency-dependent attenuation, and transmission anomaly. α(f) can be determined in three ways: Theoretical calculation, Fisher and Simmons model, and Thorp's model, which are based on experiments.

Thus, the propagation speed of acoustic signals under water is given as follows: [30]

$$q(z,s,t)=14449.05+45.7*t-5.21*t^2+0.23*t^3+(1.333-0.126*t+0.009*t^2)*(s-35)+16.3*z+0.18*z^2 \quad (2)$$

Where,

$$t=\frac{T}{10}(℃)$$

s= Salinity (*ppt*)

z=Depth (*km*)

The above expression is useful in determining the propagation speed and delay in different operating conditions.

ROUTING PROTOCOLS FOR UWSN

Tariq and Yong[31] classified UWSN routing protocols into two categories based on their localization requirement,

Table 1: Comparison of various routing protocols based on localization-based routing schemes

Protocol	Mobility	Advantage	Disadvantage
EECAR-AC[32]	Yes	Achieves reliability load handling and end to end delay	Communication over head is increased due to multiple transmission of control packets
EMGGR[33]	Yes	Parallel packet transmission over multiple node-disjoint paths adds reliability and immunity against connectivity holes	It requires geographic coordinates which adds extra overhead as well as end to end delay
RBCRP[34]	Yes	The proposed scheme achieves reliability, load balancing, and end-to-end delay	It requires the locations of the nodes which increases the overall communication overhead
ECBCCP[35]	Yes	It reduces unnecessary traffic by canceling the transmissions of previously received data	Its communication overhead is increased as a result of the control messaging incurred for communication between different entities
AREP[36]	Yes	Void problem is eliminated with the help of notification messages that are sent from the void node to the upstream node. It improves delivery ratio by proposing a smart method for relay selection	However, continuous table maintenance and updates incur relatively high communication overhead
JREM[37]	No	It improves network lifetime by distributing the network load evenly, and by avoiding the energy hole problem	Pre-defined deployment patterns are needed thereby reducing its scope. Moreover, deployment cost in deep waters may increase, as all nodes are anchored
EBOR[38]	No	It reduces collisions by setting different holding times for different relay nodes. This results in lower communication overhead, and better energy efficiency	
ACUN[39]	No	It improves the overall network level energy consumption and network lifetime	Increase in overhead
BEAR[40]	No	It improves overall load distribution by dividing the network into sectors, and achieving intrasector and intersector energy balancing	However, it has certain drawbacks, such as the 4-way handshake in the neighbor-finding phase, which increases overhead
BLOAD[41]	No	It solves energy hole problem by balancing energy consumption among nodes located at different distances from the sink node	Most nodes are exposed to rapid energy drainage due to high-power transmission. Thus, high-power transmission increases interference and contention

that is, localization-based routing schemes (Table 1) and localization-free routing schemes (Table 2). Each of the two categories as shown in Figure 2 is further subdivided into protocols that consider mobility (limited or free) and those that do not consider mobility of sensor nodes.

UASN APPLICATIONS

The areas of applications of UASN generally have a monitoring and controlling center that collects data from sinks nodes that are deployed under the water. However, routing and forwarding of data from the underwater sensors to the sink is an important technique for the deployment in any application.[1] Fattah *et al*.[51] classified the application areas of UWSN into three, namely: Scientific, industrial, and military and security as shown in Figure 3.

Scientific

a. Finding underwater information: Underwater sensor is deployed for finding information in UASN which has aided human knowledge as well as research purpose.[52]
b. Disaster prevention: Seismic activity which provides tsunami warnings to coastal areas in order to prevent disaster can be achieved is underwater sensor network system.[52]
c. Ocean sampling networks: Autonomous underwater vehicles (AOVs) are capable for interactive adaptive sampling of the 3-dimensional coastal ocean environment in which sensors can be placed in various depths in the ocean. Thus, ensuring sensing in the ocean area at different depth.[52]
d. Environmental monitoring: Environment monitoring is one of the most important applications of UASN. This include pollution monitoring, monitoring of ocean currents, and improved weather forecast.[52]

Industrial

a. Mine reconnaissance: The simultaneous operation of multiple AUVs with acoustic sensor can be used to detect mine like object.[52] The network allows for communication can exchange information between multiple AUVs for an effective cooperative countermeasure operation as shown in Figure 4.[53]
b. Monitoring of underwater pipes: UASN was used to measure disturbances due to vibrations in Langeled pipeline below 1 km on a rocky and uneven seafloor where

Table 2: Comparison of various routing protocols based on localization free routing schemes

Protocol	Mobility	Advantage	Disadvantage
EECOR[42]	Yes	It achieves high packet delivery ratios and energy efficiency	It involves repeated inspection and selection of forwarder set which my result to delay
Co-EEORS[43]	Yes	Reliability is attained by addition of acknowledgments for received packet in the protocol design	Additional overhead is added through the acknowledgments
SORP[44]	Yes	It achieves a good packet delivery ratio (PDR) in dense networks	PDR can be very low in the case of sparse networks
RECRP[45]	Yes	It achieves moderate end-to-end delay and packet delivery ratio for a small number of nodes	Excessive energy is spent during the periodic routing update phase
EDBF[46]	Yes	It reduces communication overhead	The end-to-end delivery ratio does not improve significantly
EnOR[47]	No	It achieves load balancing and increases the percentage of alive nodes	Communication overhead may be a concern in the case of dense networks:
DMR&CoDMR[48]	No	It reduces the delay induced due to long detour of packets in multi-hop routing protocols	Long detour issue may occur inside partitioned parts of the network due to multi-hop forwarding
HyDRO[49]	No	It achieves a high level of fairness by delivering data from all nodes	Voids are created when a node is in all-off stage
CACR[50]	No	Reliability is improved by incorporating a cooperative transmission scheme in every hop	Reliability comes at the cost of extra transmission, as there is one extra transmission at every hop by the cooperative relay nodes
DVOR[1]	No	It improves end-to-end delay, packet delivery ratio. It reduces communication overhead	Lack of reliability and unbalanced load distribution because it ignores link quality and residual energy

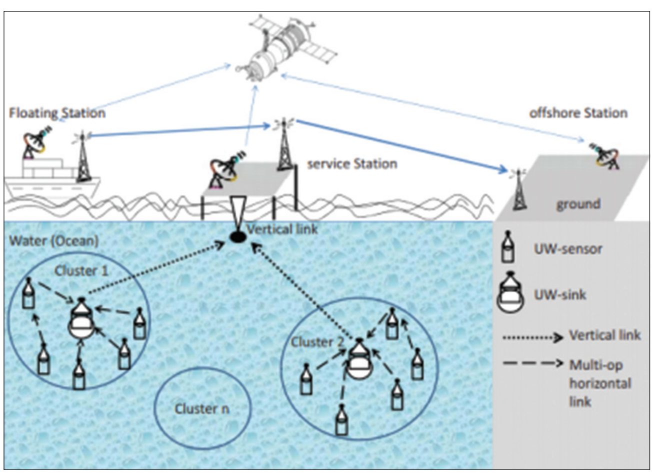

Figure 1: Underwater sensor network architecture[20]

major parts of the pipeline was not touching the seabed, thereby highly susceptible to severe vibrations during strong currents as shown in Figure 5.[55]

Military and Security

Distributed Tactical Surveillance: Surveillance and intrusion detection systems can be monitored with the aid of AUV and fixed underwater sensor. AUV can be deployed to a number of applications, such as seismic monitoring, device monitoring and leak detection, and support for underwater robots.[52]

Challenges of UASN

1. Expensive devices: The costly nature of underwater sensor devices makes supplier not able to provide the devices because are for research oriented activity.[56]
2. Hardware protection requirement: Device protection is required against water because of the extreme cost of underwater devices.[52]
3. High power for communication: Underwater sensor communication needs more power because of delay in data transfer in water. Thus, more electricity is requiring for data exchanging in water which is an issue UASNs. Other factors that can degrade the underwater communication channel are path loss noise, multipath, and high propagation delays.[52]
4. One-way communication: Underwater network communications are always one way because in standard water, transducers cannot transmit and receive at the same time.[52]
5. Propagation delay: The propagation delay is major problem in underwater sensor network. The propagation

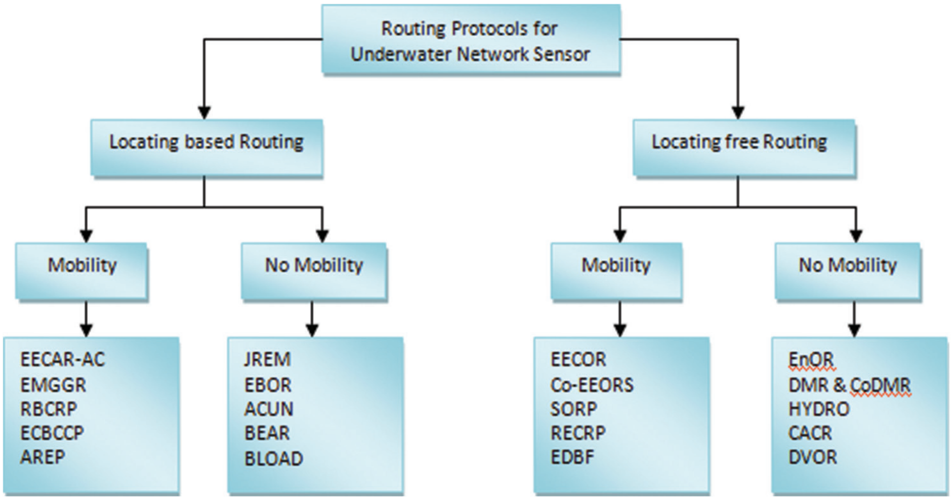

Figure 2: Classification of routing protocols based on location requirement and mobility[30]

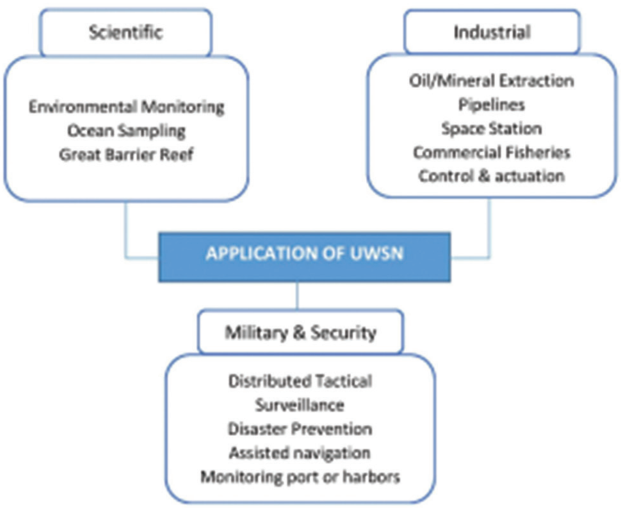

Figure 3: Underwater acoustic sensor networks application areas[18]

in underwater is higher order of magnitude than radio frequency in terrestrial sensor network.[52]

6. Localization: Finding the location of sensor in UASNs is of great challenge. This involves data labeling but some critical applications need data without any time delay.[52]
7. Limited battery power: UASNs suffer from a sensor's corrosion and pollution due to the fact that electronics components, like battery, tend to decrease strength faster under extremely low temperatures found in deep underwater. This results to less lifetime of UASN and underwater sensor battery power.[52]
8. Bandwidth size limitation: In the UASNs, bandwidth limitation is of great concern.[52]
9. Reliability: Reliable delivery of sensed data to the surface sink is a quite challenging compared to forwarding collected data to the control center.[57]

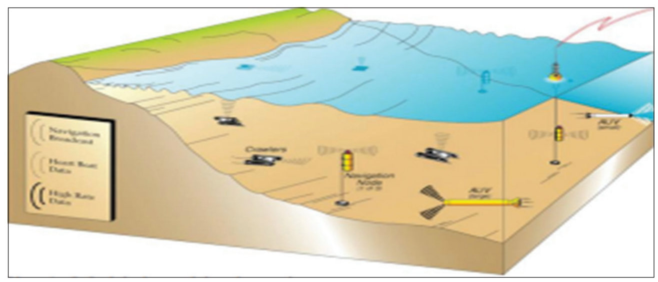

Figure 4: Mine counter measure system[54]

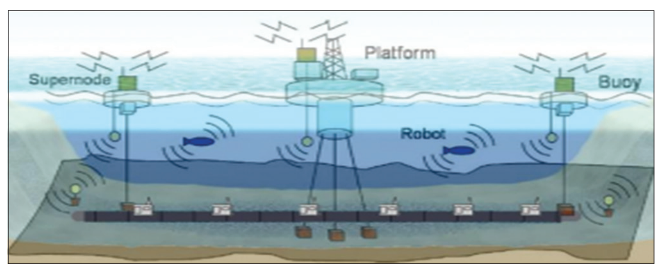

Figure 5: Underwater acoustic sensor networks pipeline monitoring[55]

10. Temporary losses: Packet lost temporary as a result of connectivity time and packet sending time.[52]

CONCLUSION

In this paper, we have discussed the communication architecture, propagation models, routings protocols, applications, and challenges of UASN. UWSNs have a vast potential in exploring the oceans using acoustic communication link because of its relative low absorption over long distance in water. Underwater environment in WSN poses great challenges as compared to terrestrial WSN; hence, network models need to be done with utmost care and efficient routing protocols.

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