Wireless Personal Communications (2019) 104:995–1022
https://doi.org/10.1007/s11277-018-6064-z

Protocol Stack of Underwater Wireless Sensor Network: Classical Approaches and New Trends

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Published online: 28 October 2018

Abstract

The oceans and rivers remain the least explored frontiers on earth but due to frequent occurrences of disasters or calamities, the researchers have shown keen interest towards underwater monitoring. Underwater Wireless Sensor Networks (UWSN) envisioned as an aquatic medium for variety of applications like oceanographic data collection, disaster management or prevention, assisted navigation, attack protection, and pollution monitoring. Like terrestrial Wireless Sensor Networks (WSN), UWSN consists of sensor nodes that collect the information and pass it to sink, however researchers have to face many challenges in executing the network in aquatic medium. Some of these challenges are mobile sensor nodes, large propagation delays, limited link capacity, and multiple message receptions. In this manuscript, broad survey of issues concerning underwater sensor networks is presented. We provide an overview of test beds, routing protocols, experimental projects, simulation platforms, tools and analysis that are available with research fraternity.

Keywords UWSN · Applications · Open issues · Protocol stack · UWSN projects

1 Introduction

Nearly 70% part of our planet is covered by water but most of this is unexplored. Recently, the exploration is significantly increasing in this area. Not only has it been rich in valuable resources but with time it's playing a significant role for defense, transportation like ships, natural resources like oil pipelines. The most important concern for the researcher is to handle such a big data of naturally existing underwater area like oceans, sea etc. The developers have been successful to some extent in collecting and analyzing the extensive underwater environment by developing various UWSN protocols. The past research work in the field of UWSN as described in area background below is performing as a basis for the future research [1–3].

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In 1826, Lake, Charles and Daniel with their experiment evaluated sound velocity in water. This research laid the foundation for underwater acoustic technology. Then Lewis in 1906 invented Sonar type listening device. In 1915, Paul invented sonar type device to locate submarine by using piezoelectric properties of the quartz. These inventions led the discovery of geological resources like gas, oil, detecting and tracking fish banks etc. with the help of depth measuring technique by sonar devices. In 1990s in aquatic medium, the underwater vehicles and surface buoys coordinated the data in the form of signals. For the past twenty years, many researchers have explored underwater wireless technologies to design number of applications for the purpose of underwater monitoring and surveillance [4–6]. Even if many authors have published quality review and survey papers in many separate areas of UWSNs, still the scope in this paper is distinguished from them in many aspects. Various survey and review papers are available, where the authors conducted a survey of localization schemes, applications, and routing protocols in underwater and acoustic communication [7–10]. Some others addressed routing issues and challenges with ocean monitoring by networking of underwater communication devices. Further, some authors have discussed localization algorithms and energy efficiency [11–14].

In comparison to traditional sonar/radar systems UWSN can provide more accuracy, enable detection and monitoring more specifically. But this area requires exploration by researchers like WSN. Although certain aspects of WSN can be applied to UWSN but sensor network used for UWSN differs from general land based sensor networks. Underwater channels remain challenging due to variable physical properties of aquatic medium [15–17].

1. Communication method is different because radio waves don't work effectively in underwater like on ground, that's why UWSN uses acoustic signal while WSN uses radio waves.
2. For these networks power strength of signals required varies, acoustic signal moves through dense area and covers longer distance in comparison to radio signals where processing at receivers is not that complex.
3. Unlike terrestrial sensor networks dense deployment of sensors is not easy in underwater sensor deployment as sensors may fail due to number of reasons like underwater corrosion or fouling etc.
4. Besides this underwater sensors having limited battery power because they are extremely difficult to recharge due to non-availability of solar energy to regenerate power like grounded sensor networks.
5. Propagation delay is another major factor because the propagation speed of underwater signal is about 1.5×10^3 m/s whereas speed of radio signal is 3×10^8 m/s.

The research work carried out so far is providing a base and support to review the existing communication protocol.

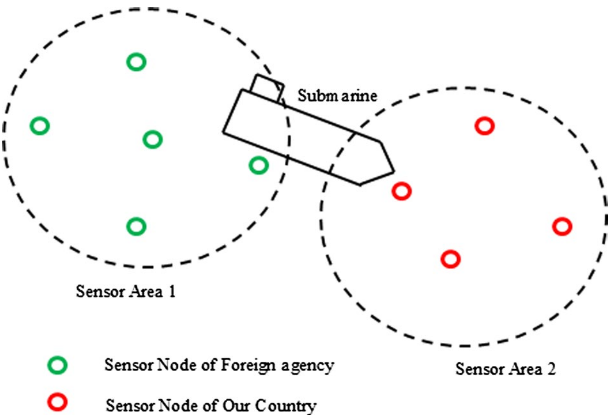
The main goal of underwater acoustic network (UAN) is to monitor the river or oceanic environments by exchanging information. It seems to be a costly affair if data is collected manually by divers moving under the sea for hours. Whereas an underwater sensor network can also be deployed to monitor and record pressure, temperature, pollutants from off-shore or underwater ecosystem [18–21] There exists broad range of applications for UWSN which can be classified into the following:

1. *Assisted Navigation* Different types of seen or unseen obstructions are present in sea. Assisted navigation can be used to detect the obstructions like shoals, mooring positions in the sea. For example assisted navigation could prevent the loss of the ship Titanic by detecting the correct position of iceberg. To find these types of disasters, assisted navigation can be done by sensor networks.
2. *Disaster Prevention* UWSN deployed under the sea can detect the movement of tectonic plates that can cause underwater disasters like volcanos, sea-quake and tsunami. Thus the timely information of the movement of tectonic plates can prevent the loss of life's and property.
3. *Environment Monitoring* Pollutant from land, human activities affecting ocean ecosystem, monitoring of winds, biological monitoring like tracking of sea animals are other possible underwater environmental monitoring applications.
4. *Military Purpose* Figure 1 describes that under water sensor network is used to detect the foreign submarine or ships etc. when they try to enter in restricted area. The application is used by military forces in timely detection of foreign sub marines etc. to prevent the underwater terror attack.
5. *Mine Exploration* Optical sensors and acoustic sensors with Autonomous Underwater Vehicles (AUV) collectively can detect mine based upon sensed data.
6. *Oceanographic data sampling network* Sensors of networks and AUV can collect data from underwater environment. If they use mobility then the task becomes easy and helps them.
7. *Tactical Surveillance* Sensor nodes (both static and mobile) monitor areas for surveillance, targeting, intrusion detection system to detect and classify divers, autonomous vehicles.
8. *Underwater Exploration* The exploration which is difficult to monitor manually due to vast unknown area, unpredictable underwater activities. UWSN explore such kind of activities like exploring oilfields, determining routes for laying underwater cables.

1.1 Motivation

A lot of research is going on to explore UWSNs as still there are some issues have left unresolved. In order to summarize, the current technologies, methods, to solve problems, their limitations and challenges along with open research issues for various layers are

Fig. 1 Submarine detected by sensor network



presented over here [22, 23, 78]. We have documented these current issues and challenges associated with underwater communication. The main motivation behind conducting the review on underwater sensor networks is lack of the review on the schemes of protocol stack, the current issues associated with them and further unresolved challenges.

This document is a presentation of brief review over main issues and challenges of research literature on UWSN. The purpose of this article is to discuss each and every aspect on UWSN, for further it is organized as follows: Sect. 1 makes all of us familiar with UWSN and the main terms associated with this. Further, Sect. 2 will be consisted of UWSN architectures and issues associated with them like communication architecture and UWSNs layered approach. In Sects. 3–6 we discuss data link layer, network layer, transport layer, and application layer issues in UWSNs respectively. In the next Sect. 7 we have raised some security issues in the presence of underwater environment. Section 8 introduced here for simulation platforms and tools, simulation studies, experimental studies, test beds/trials. Also the simulation analysis is done in Sect. 9. In Sect. 10 we will explore some of the new emerging areas of UWSNs with the research possibilities in those fields while in Sect. 11 we will draw the conclusion.

2 UWSN Architecture and Issues

Usually sensor nodes are dispersed in the network with the capability to collect and transmit data to end users [24–26]. How this communication actually happens and the protocol stack used by the sink and all sensor nodes in layered approach is shown below.

2.1 Communication Architecture of UWSN

Generally depending upon localization, and real time data transfer UWSN is divided into two parts:

1. Long-Term Non-Time-Critical Aquatic Monitoring

In these types of network, nodes arrange themselves compactly to cover geographical area of an aquatic medium. Energy saving is the primary issue here because energy of the nodes drain out more quickly and it is difficult to recharge them in underwater environment. Monitoring and detection of underwater pollution or oil gas leakage are some of the practical applications with such network.

2. Short-Term Time-Critical Aquatic Exploration

Real time data transmission plays efficient role in such network, because of short range communication whereas energy efficiency and localization are not of much concern like other networks. Such types of network are used in military operations for detection of AUVs' like submarine.

Whereas, if we talk about network topology, UWSN architecture can be classified into 3 categories

(a) Static 2D Underwater Acoustic Sensor Networks are used for Ocean Bottom Monitoring. Environmental monitoring and underwater plates monitoring are its typical applications.
(b) Static 3D Ocean Column Monitoring is used for Surveillance applications or monitoring of ocean phenomena like pollution etc.
(c) Three Dimensional Networks of Autonomous Underwater Vehicles (AUVs).

Mainly, an underwater communication network is formed by the cooperation among several nodes uses bidirectional acoustic links. Each and every node is independent for sending/receiving/forwarding messages. Information collected by underwater sensor nodes is communicated to surface buoy like ship (which can be static or mobile) placed on water surface equipped with both, acoustic and RF modems by using wireless acoustic links [27]. Furthermore, surface station transmits data to command center placed on-shore ground surface via satellite as shown in Fig. 2. Command centers communicate with other command centers on ground surface with the help of satellite forming communication network.

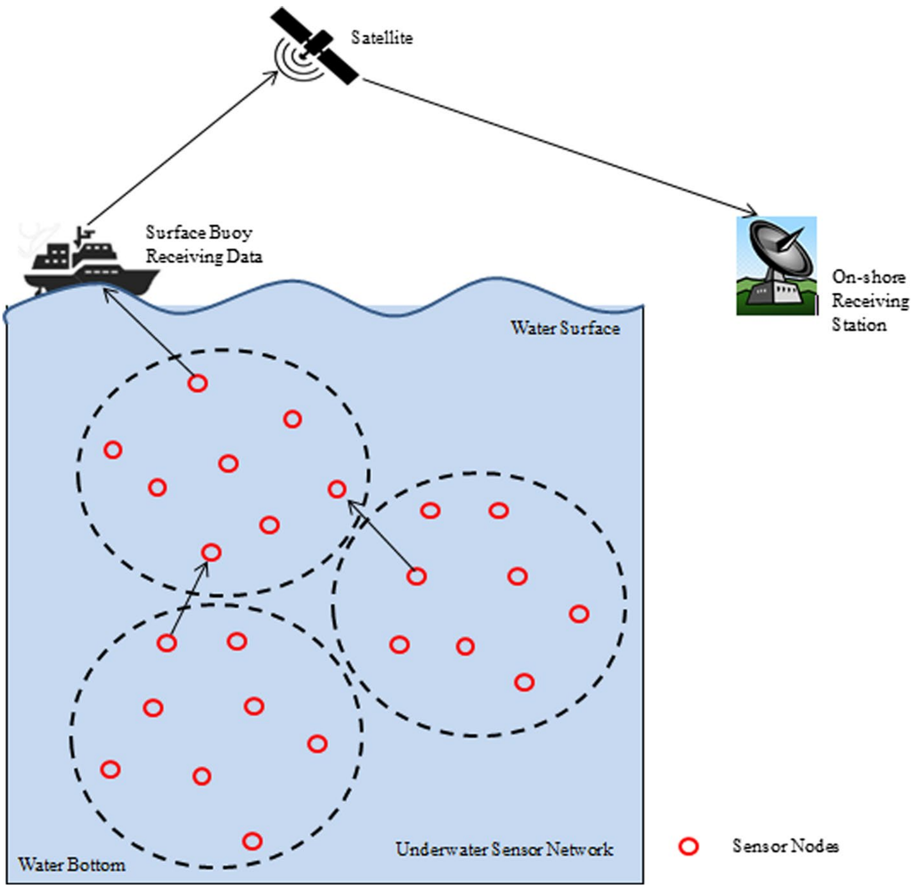


Fig. 2 Underwater wireless sensor network communication architecture

2.2 Layered Architecture of Protocol Stack for UWSN

Protocol stack used by underwater sensor nodes including header node, sink node is given in Fig. 3. Considering the critical underwater sensor network, the stack for underwater sensor network should constitute physical layer (data transmission and reception), data link layer (MAC protocols), network layer (routing protocol), transport layer (transport protocol), and application layer (data processing). This protocol stack should also combine security service, consumption of power, and distributed localization with high efficiency of bandwidth and time synchronization.

Nowadays UWSN are difficult to establish because it incurs high cost apparatus and poor energy efficiency. Their low distance operating range and non-real time synchronization, suggested the researchers to develop the protocols without these flaws. Here, protocol stack states same issues along with security service.

1. *Physical Layer* Physical layer takes care of transmissions and receiving techniques. Acoustic signals are the most obvious choice for underwater communication because

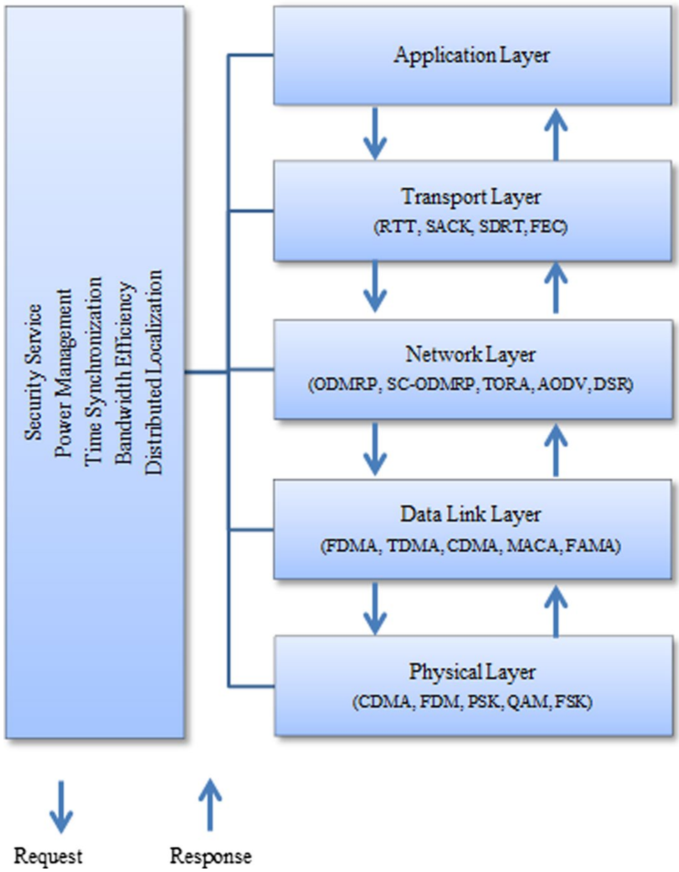


Fig. 3 Layered architecture of protocol stack for UWSN

radio waves are not able to propagate longer distance through this environment. These signals also support broadcasting in a shared medium.

2. *Data Link Layer* (*DLL*) DLL addresses issues like noise, multi path propagation and node battery failure which are major factors that influence acoustic communication in shallow water, causes fading of communication signals. Various communication methods being proposed to overcome these problems like MACA, DSSS, FAMA, FAMA-CF etc. and some are under process.
3. *Network Layer* Network layer is concerned about routing of data which is transferred by transport layer with the help of routing protocol. Since the underwater network environment is too dense where GPS can't be enabled and sensor nodes are non-chargeable operated with limited bandwidth, MAC protocol must be power aware with better time synchronization to lower propagation delay and lesser error rates.
4. *Transport Layer* It is responsible for end-to-end communication over underwater network. It creates logical communication among different running application processes.
5. *Application Layer* Different application software are developed on application layer. Also the existing application layer software is utilized on this layer to maintain the flow of data between sensors.
6. *Security Service* This plane is responsible for maintaining integrity as well as confidentiality of data and availability of all authentic messages in the presence of resourceful adversaries. It possess many counter measure like use spread spectrum techniques with low duty cycle and tamper-proofing at physical layer, error correcting code at DLL layer, false routing detection at network layer, cryptographic approach at application layer.
7. *Power Management* To increase the network lifetime, a good synchronization protocol is to be used by this plane. Best solution for this is to keep nodes in sleep and active mode periodically with some specified time period and choose the header node with highest energy.
8. *Time Synchronization* This plane tackles delay and time synchronization problem between network components, so that real time application scenario should be there.
9. *Bandwidth Efficiency* In under water networks acoustic band is limited due to absorption. Most acoustic systems operate below 30 kHz.
10. *Distributed Localization* It assigns the responsibility to inform each node about its neighbors and also the best suited neighbor to send data packet to sink.

2.3 QoS Issues of UWSN

With recent developments in the area of communication in aquatic medium, researchers get attracted towards fulfilling the QoS (Quality of Service) requirements. However it is pertinent to mention here that providing full support of QoS is very difficult because of highly unreliable nature of node and dynamic wireless links [28, 29]. Availability of networks is immediately affected by quality of service. QoS topology control approaches can be categorized in two parts centralized and distributed. It is preferable to use distributed topology control approach because centralized algorithm introduce communication overhead for large scale sensor networks [30–32]. The parameters of QoS are categorized into application specific and network specific categories. High QoS refers to maximum network lifetime and proper message delivery. Topology control is one of the efficient ways to enhance the quality of service which is beneficiary in lower down propagation delay, network lifetime extension, increase in successful transmission, and improvement of energy efficiency.

Cao and Yang considered end-to-end delay, residual energy, and given a multi QoS optimization distributed topology control algorithm [33]. A lot of QoS approaches come under considerations from last decade like LEACH (Low Energy Adaptive Clustering Hierarchy), MIN-RC, I-LEACH, EE-LEACH-MIMO, LEACH-MF, TDMA, SDRT, multipath routing, network coding, HBER (High Bit Error Rate) but all fainted due to some reasons. The main reason behind these is the distance oriented bandwidth and variable topology of UWSN. A researcher proposed SAA a distributed strategy adjustment algorithm to achieve and optimize coverage, connectivity, and energy consumption, average delay of single hop, path bandwidth, and transmission success ratio by better simulation results.

2.4 Energy Efficiency Issues with UWSN

For every sensor network it is important to improve the life of sensors because if battery of any node drains out it will stop working. With the passage of time the increasing growth of stopped nodes will result into shrinking of sensor network. As we earlier said that in case of underwater sensors where we cannot use solar energy, it is also very difficult to change the battery, specifically when nodes are deployed densely. One possible solution is to save energy in every software and hardware solution for the network. Secondly, to use combined chemistry and mechanical methods to generate energy by itself. Thirdly use best technology in battery like Lithium-ion in comparison to others like Nickel Cadmium etc. Another way is to use sleep and wake mode of operation. Fifth way is that when the node battery is near to end the node will come up over the water surface by the help of any balloon and gets recharge by solar power. Cui et al. in his paper proposed a technology named Multipath Power control Transmission (MPT) for applications that are time-critical in UWSN by avoiding retransmission at the intermediate nodes [13]. Climent et al. proposed a routing protocol EDETA-e (enhanced-Energy-efficient aDaptive hiErarchical and robusT Architecture) in his research which minimizes energy consumption [14]. Due to satisfactory results, EDETA-e is now going to implement with real nodes instead of simulation. Still, it is required to develop new energy efficient protocols for UWSN to give better performance.

2.5 Fault Tolerance Issues for UWSN

Fault tolerance is a property that urges the system to remain operative even in case of failure of its one or more components. Xu et al. presented Fault Tolerant Routing (FTR) protocol, as an energy efficient protocol with high adaptability due to less end-to-end delay, and more packet delivery ratio. EDETA-e protocol supports more than one sink to provide fault-tolerant mechanism [15].

3 UWSN MAC Layer Issues

Due to different underwater environment, terrestrial MAC solutions can't be applied here. The main characteristics of an underwater communication, like attenuation, propagation delays, limited bandwidth, error rates, and energy consumption impose unique challenges for Medium Access Control (MAC) [34]. ALOHA is the simplest MAC protocol since it does not care about channel status or packet delivery success producing a huge number of collisions. Existing MAC solutions were based on Code Division Multiple

Access (CDMA) or Carrier Sense Multiple Access (CSMA), Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA). However, FDMA was used in 1998–1999 by SeaWeb but it was found not suitable due to narrow bandwidth available from acoustic channels and TDMA proves limited bandwidth efficiency. CSMA was used in 2000 by SeaWeb but its suitability is affected due to increased energy consumption overhead of RTS/CTS packets. CSMA based protocols are vulnerable to both hidden and exposed terminal problems. To reduce this problem, proposals of MAC include Multiple Access Collision Avoidance (MACA) (uses RTS/CTS/DATA packets) and MACAW (uses RTS/CTS/DATA/ACK packets) [35]. FAMA avoids data packet collisions (by extending the RTS/CTS packet durations). Slotted FAMA avoids propagation delay (by adding timeslots to FAMA protocol). Improvement over Slotted FAMA is Distance Aware Collision Avoidance Protocol (DACAP) which minimizes handshake time, reduce power consumption. The techniques Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS) were devised over CDMA but DSSS having the limitation of affecting the maximum spreading factor. Pompili et al. recommended a distributed MAC protocol based on CDMA called UW-MAC (by setting optimal transmit power and code length) exploiting high channel re-use and retransmissions of few packets [17]. Jornet et al. proposed Focus Beam Routing (FBR) protocol that finds path between the randomly placed nodes in network but having the limitation that some short sized packet collision can happen [18]. They also proposed a time-critical Multi-path Power-control Transmission (MPT) scheme to minimize energy consumption and packet delay. But it is having the limitation of high traffic density and nodes collision due to this. Van et al. designed a MAC protocol for underwater localization and time-synchronization. In this scheme the reference nodes used are the static one and the un-positioned nodes i.e. blind nodes are being localized with the help of beacon messages. These beacon messages occur in scheduled (when modulation rate is low and less energy consumption) and unscheduled communication (when localization and time synchronization are performed faster) methods [19]. Lee et al. proposed Unicast Based Gradient Routing Protocol (UGRP) to support asynchronous duty-cycle MAC protocol to provide better network lifetime. Asynchronous duty-cycle MAC protocol was not able to send advertising messages, but now with the help of UGRP it is able to do this. There exists a limitation that UGRP has to depend upon unicast transmission to inform neighbors about updated gradient [20].

4 UWSN Network Layer and Routing Issues

The network layer in UWSN enables the routing packets to move to the appropriate destination. The routing packets while moving to the destination travel through various hops, for which a routing protocol is required. Network layer is responsible for finding and making sure that the path chosen is appropriate [36–41].

In large network field, it is not easy for pair of nodes to communicate directly. There must be a multi hop communication, in which intermediate nodes will forward messages to final destination.

Long time ago a proposal of routing protocol was found as, TDM (Topology Discovery Message) on demand propagation method was devised in 2001 which was based on reactive routing protocol but it was having the limitation that it can only work on full duplex channel [21]. As stated by Akyildiz in 2005, proactive routing protocols in which predefined routing path exist like DSDV (Destination Sequenced Distance Vector), OLSR (Optimized Link State Routing Protocol) produces a large signaling overhead to establish route [10]. Similarly reactive routing protocol in which on demand route is decided as AODV (Ad hoc On-demand Distance Vector routing), DSR (dynamic source routing) that incurs higher latency. Geographical routing protocol like GFG (Greedy Face Greedy routing), PTKF (Partial Topology Knowledge Forwarding Routing) fails to work efficiently in aquatic medium as GPS (Global Positioning System) hardly works underwater especially area with larger depth.

In 2006, Vector-Based Forwarding (VBF) was presented where the positions of source, forwarder, and destination is carried by each packet. Packets are forwarded along redundant paths, being robust against node failure and packet loss. Finally a self-adaption algorithm is also given to upgrade the results of VBF. Another proposal in 2006 was established using the concept of virtual circuits. It founds a priori between source and sink, so that each data packet travels on identical path as the connection. For this purpose centralized coordination is required at the sink node level however it reduces the flexibility of the routing structure. In order to enhance the reliability of the network occurred because of expected node failure, algorithm is used to identify two paths from each source to destination that are primary and backup. Some other proposal of Multipath Virtual Sink, Resilient Routing, Location Aware Source Routing (LASR) were also proposed in 2006, which includes location and link quality awareness but requires special network setup and operates for small networks only. Over to these protocols, in 2007 we were present with packet cloning, Distributed Underwater Clustering Scheme (DUCS), Information Carrying Routing Protocol (ICRP), Distributed Minimum Cost Clustering Protocol (MCCP) having self-organizing algorithms with sleep and wake-up scheme requires only one hop transmission means do not support multi hop transmission. Focused Beam Routing Protocol (FBR), Directional Flooding-Based Routing (DFR), Reliable and Energy Balanced Routing Algorithm (REBAR), Depth Based routing (DBR), Energy Efficient Routing Protocol (EUROP), Underwater Wireless Hybrid Sensor Network (UW-HSN), Multi Sink Opportunistic, Robustness Improved Location Based Routing (LCAD), and Adaptive Routing were developed in 2008 to overcome the disadvantages of before said protocols with new approaches but they were not good enough in terms of performance, data delivery efficiency, bandwidth efficiency, energy efficiency, require nodes with special hardware and still not reliable.

Dynamic Hop-by-Hop Dynamic Addressing Based Routing Protocol (HH-DAB) devised in 2009 utilized HOP-IDs assigned to every node based upon their depth position. This minimized routing table overhead, can handle multiple sink at a time with a failure of high end-to-end delay it makes underwater monitoring critical.

Researchers tried a lot to overcome these previous problems and invented Hydro-cast, Temporary Cluster Based Routing (TCBR) in 2010. They used 3-hop neighbor to balance energy by forming temporary clusters. Their packet transmission cost was much higher as well as they improved energy efficiency and bandwidth efficiency but not much satisfactory. Wahid et al. proposed an Energy efficient Routing Protocol based on Physical distance and Residual energy (ERPPR) to prove it energy efficient by utilizing physical distances from sensor nodes to sink. They also considered residual energy in order to extend network lifetime [22]. In 2012 Evolutionary Based Clustering Routing Protocol (ERP) was proposed. They redefined fitness function (i.e. Transmission Distance or simply distance) to minimize network energy consumption by solving two clustering purposes that is intra-distance and inter-distance. It was proved to be of longer network lifetime, better way energy consumption. But this protocol is having less stability awareness and requires future research work over this [42–44].

5 UWSN Transport Layer Issues

Reliable transportation of event features is required in underwater communication. This is done at transport layer. Here we will discuss the issues and challenges for developing transport layer protocol that is reliable as well as efficient in UWSN. Some WSN transport layer solutions will also be discuss with their shortcomings to apply on underwater communication. In a network, reliable event detection at sink node should depend on the data collected from all source nodes and not on any individual report from them. If reliable transport mechanism is not present then event detection cannot be done due to underwater challenges. Hereby in UWSN, end-to-end reliability concepts are not applicable and a reliable event transport mechanism is required [45]. Transport layer is responsible for reliable transportation of event features and also leads to congestion control and flow control. Congestion control prevents the network from being congested and flow control keeps track of network devices from being overloaded by data transmission. Most of the TCP implementations are not suited for underwater communication due to its environment. As it is a well-known fact that functionality of Flow control depends on window based mechanism which further depends upon the accurate estimation of Round Trip Time (RTT), however, in case of underwater communication timeout of window based mechanism becomes difficult to set as RTT is variable. Suitable transport protocols based on transmission rate are required for challenging environment of UWSN. Packet drop occurs in the network either due to network congestion or high bit error rate of acoustic channel. The network congestion does not allow more packets to inject into the network therefore, transmission rate decreases with packet loss in the network. Another reason for packet loss is bad channel quality that further reduces the transmission rate. Due to these reasons it is desirable to get new strategies for underwater flow control and reliability. Some solutions in WSNs are proposed to solve these problems, like event-to-sink reliable transport (ESRT) scheme that detects event more reliably by spending minimum energy. These protocols are based upon spatial correlation. In WSNs nodes are deployed densely and their readings may be correlated. Whereas in UWSN, nodes are not so densely deployed being complex as well as costly, thus sensor readings are not significantly correlated.

6 UWSN Application Layer Issues

The number of application areas of UWSN have already been discussed in the initial part of this document however it is still remain to be explored further to develop approaches for supporting these applications.

Application layer provides network management protocol that creates hardware and software details of the lower layers in a transparent manner to manage applications. It is being given the responsibility of maintaining an interface to query the sensor network completely. It also assigns tasks and advertises data and events [46, 47]. A deep knowledge and understanding of application areas is crucial to develop application layer protocols. Peng et al. presented Networked Acoustic Modem System (NAMS) with a combination of high-speed OFDM modem and underwater network protocol stack to provide high speed, reliable and efficient communications in underwater environments [24].

Further, the comparison of various UWSNs' protocols is shown in Table 1 depicting the mechanisms used, merits and demerits.

Table 1 Comparison of various UWSN's protocols

S. no.	Year	Layer	Authors	Proposed mechanism	Simulation platform used	Performance parameters	Benefits	Limitations
1.	2007	Network layer	Domingo et al. [73]	DUCS	NS2	Routing overhead, packet delivery ratio	Minimized proactive routing and delivery ratio	High energy depletion
2.	2007	MAC layer	Pompili et al. [17]	UW-MAC	NS2	Energy consumption, packet drop, delay, packet delivery ratio	Optimal transmit power	Time complexity
3.	2008	MAC layer	Jornet et al. [18]	FBR	NS2	Energy consumption, active nodes	Better route establishment	Node mobility issues
4.	2010	Network layer	Ayaz et al. [74]	TCBR	NS2	Packet delivery ratio, end to end delay and power consumption	Reduced energy consumption	Node mobility problem
5.	2010	Network layer	Kim et al. [55]	MARPCP	NS2	Delay, throughput	Good performance ratio	More overhead
6.	2011	Network layer	Huang et al. [75]	SHC	C++	Energy consumption, packet drop, delay, packet delivery ratio	Outstanding data collection results and active nodes	Higher energy depletion
7.	2011	Transport layer	Wu et al. [76]	MLAS	NS2	Aggregation latency	Decreased latency	Relay selection overhead
8.	2012	Network layer	Manjula et al. [61]	CDA	NS2	Energy consumption	Low energy consumption	Resource utilization problem
9.	2012	MAC layer	Lee et al. [20]	UGRP	NS2	Network life-time, packet delivery ratio	Less redundant transmission	Energy consumption
10.	2013	Transport layer	Dhurandher et al. [39]	ERMTG	AQUA-GLOMO	Packet delivery ratio, path energy, network energy, delay	Better delivery ratio and lower energy consumption	More computation overhead

Table 1 (continued)

S. no.	Year	Layer	Authors	Proposed mechanism	Simulation platform used	Performance parameters	Benefits	Limitations
11.	2013	Network layer	Tran et al. [67]	EDAA	QualNet5	Data loss, data sent ratio	Minimized packet loss and data redundancy	Similarity function here is not satisfactory
12.	2014	Network layer	Tran et al. [69]	RBC	QualNet5	Energy consumption, throughput, Data received ratio	Less energy consumption and high-throughput	Node mobility problem
13.	2015	Application layer	Harb et al. [46]	K-means and ANOVA	NS2	Energy consumption and data sent ratio	Minimized data redundancy	Higher energy depletion
14.	2015	Application layer	Ilyasa et al. [47]	SEDG	NS2	Delay, energy consumption, network throughput, packet delivery ratio	Increased network life and packet delivery ratio	Data collection efficiency issue
15.	2016	MAC layer	Nowsheen et al. [62]	PRADD	NS2	Packet delivery ratio, routing overhead, energy consumption, location estimation error	Lower overhead and energy consumption	Deficiencies in dynamic data transfer
16.	2017	Network layer	Kartha et al. [77]	DTMSM-NZ	OMNET++	Packet delivery ratio, latency, throughput, network lifetime	Lowest mobile sink travel time	Involve enormous overhead at mobile sink

7 UWSN Security Issues

In WSNs security requirements are confidentiality, availability, authentication, authorization, integrity and nonrepudiation. UWSNs are more prone to attacks and threats, in each layer of communication protocol. These threats and attacks can be DTS (Data threats security) attacks, DoS (Denial-of-service) attacks, physical attacks, impersonation attacks and replication attacks. DoS attacks can be classified as jamming, wormhole attack, sinkhole attack, HELLO flood attack, acknowledgement spoofing attack, selective forwarding attack, and Sybil attack. Due to possibilities of so many attacks security approaches are required at every step of communication which Izadi et al. classified as secure time synchronization, secure localization, and routing in UWSNs [48].

Time Synchronization is mandatory for UWSN, where nodes will adjust their schedules to transfer data. Precise time synchronization is difficult in UWSN due to its environment but still some protocols designed for this. Tri-Message protocol is designed for high-latency networks. MU-Sync is a cluster based synchronization protocol. It gathers the local time information then performs the linear regression, based on this clock skew estimation takes place. But none of these schemes considered security [49].

UWSNs possess high and variable propagation delay, to synchronize these nodes we have to measure time. A new approach is desired for this estimate of time.

8 Experimental Studies and Projects in UWSN

Only theoretical concepts are authenticated until unless they are proved on real time scenario, but sometimes we are not able to get this real time scenario may be due to higher cost of sensors, aquatic channels, and lack of the environmental conditions etc. So, we have moved towards simulation of these tools.

8.1 Simulation Platforms and Tools

Simulation is the act of imitating the behavior of some situation or some process by means of something suitably analogues. In other terms it is the technique of representing the real world by a computer program [50]. By using simulator we can decrease the cost of our experiment. A lot of simulation tools are present now days, some of which are paid and some are freely available. For UWSNs we need such type of simulator which possesses the features and behavior like underwater environment. Casari et al. designed their own simulator to test underwater networks [26]. Peng et al. [27] and Kumar [51] used MATLAB for their experiment. Simulation was performed on NS2 by Nimbalkar et al. [28]. NetSim, a simulator for underwater acoustic networks is described by Montana et al. [29]. Torres et al. simulate sensor network nodes on a PC by using TOSSIM [30]. Goetz et al. carried out the evaluation of the network performance by using the nsMiracle simulator (an enhancement of NS2) [31]. Kim et al. used LinkQuest Inc.'s UWM1000 model for underwater acoustic modem energy model [32].

8.2 Test Beds for Underwater WSNs

Kredo et al. studied underwater sensor networks implementing two test beds. They have used scheduled MAC algorithm in one test bed and unscheduled MAC algorithm in the other [52]. Proctor et al. developed a test bed for studying underwater network in 2010 called as Ocean Technology Test Bed (OTTB) [53]. Torres et al. presented a research platform that allows developers to easily implement and compare their protocols in an underwater network and configure them at runtime. This software defined as Underwater Acoustic Networking plaTform (UANT) to aid development of underwater acoustic networks [30]. Aqua-Lab can be used to experimentally evaluate algorithms and protocols designed for underwater sensor networks together with Micro-Modems developed by WHOI (Woods Hole Oceanographic Institution). They provide acoustic communication channels that are close to field test setup. Peng et al. [27] showed the design, implementation and measurement of AquaLab, an underwater acoustic sensor network lab test bed. Aqua-TUNE is an experimental field test approach used by Peng et al. [27].

The test bed shown in Fig. 4 is a model of the most important part of an underwater network. It constitutes the equipment's' like speakers, hydrophone, modem and sound mixer for underwater communication. To observe the communication in an aquatic medium, the test bed model is put in the water tank and sensor nodes/hydrophone are deployed. The modem and the sound mixer sends signal in the form of sound using underwater speaker where the signal is analyzed by the hydrophone that further transmits the recorded data of the received signal to the micro modem.

One of the key objectives of this document is to encourage developers about the efforts required to develop real projects. Sometimes simulation is not just enough and actual work is required to take place so that accurate readings can be observed. Below given table is a list of research projects undergone and in progress related to underwater communication tested with ecofriendly equipment (Table 2).

A lot of underwater experiments or real test projects are running and hundreds of projects over ocean engineering, underwater acoustic communication, underwater node energy maintenance, AUVs development, data collection strategies etc. are running by various labs all over the world. This list is just the overview of some of the projects undergone and running these days with their field and link to see.

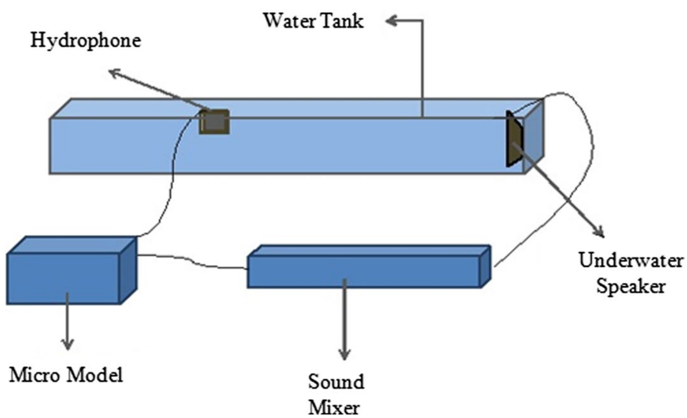


Fig. 4 Test bed setup

Table 2 Research projects/experiments in UWSNs

S. no.	Projects/experiments UWSN	Research Lab	Objectives of project	1991–2001	URL
1.	Autonomous underwater vehicles	AUV Lab @ MIT Sea Grant	It was critical to develop unmanned vehicles even in underwater environment; it was done under this project	1987–2007	http://auvlab.mit.edu/
2.	Autonomous ocean sampling networks II	AOSN Lab	The major concern of this project was to quantify the gain in predictive skill for principal circulation trajectories, transport at critical points for remote adaptive sampling using a network of autonomous underwater vehicles	2006	http://www.princeton.edu/dcsl/aosn/
3.	MBARI ocean observing systems (MOOS)	MBARI Lab	Continuous observation of ocean systems manually, is not an easy task. It requires a lot of labor. To decrease the labor involved and to make instrument development easier by the help of collected data was done under this experiment	2006	http://www.mbari.org/rd/projects/2006/moos/900026_SENSORS_06.html
4.	Shore side data system	MBARI Lab	Data collected under MOOS experiment was no longer supportable; it required visualization and support for new data. To ensure this shore side data system was designed	2006	http://www.mbari.org/rd/projects/2006/moos/600031_ssds_06.html
5.	OMEGA II (Ocean Microbial Energy Generation Assessment)	MBARI Lab	Main concern of this project was to explore the latency of energy in deep-ocean sensors using biofuel cells	2007	http://www.mbari.org/rd/projects/2006/moos/900406_OMEGA_06.html
6.	Long-term broadband seismic observatory in Monterey Bay	MBARI Lab	The project in particular developed interfaces that will function as blueprints for the linking of a number of analog, simple and complex serial devices as cabled viewpoints for upcoming era	2007	http://www.mbari.org/rd/projects/2007/observatories/200009_seismic_07.html

Table 2 (continued)

S. no.	Projects/experiments UWSN	Research Lab	Objectives of project	1991–2001	URL
7.	Monterey Accelerated Research System (MARS)	MBARI Lab	The importance of this integrated system was to commission and check the system before lay down of system cable	1991–2001	http://www.mbari.org/rd/projects/2007/observatories/900225mars_07.html
8.	MOOS Upper-Canyon Experiment	MBARI Lab	Under this experiment MBARI Lab engineers find out how to best place the equipment near the canyon to monitor even a little action without getting destroyed by the high energy events	2008	http://www.mbari.org/rd/projects/2008/observatories/moos_uppercanyon_08.html
9.	MBARI Axial Seamount Experiment Feasibility Study (MASE)	MBARI Lab	Feasibility study for the survival of experiment instruments even in the presence of Volcano was thought under this experiment	2008	http://www.mbari.org/rd/projects/2008/observatories/mase_08.html
10.	Wave Energy Extraction for Vertical Profiling	MBARI Lab	This project was to examine the potential to recover sufficient power from vertical profilers	2008	http://www.mbari.org/rd/projects/2008/observatories/waveenergy_08.html
11.	Reef explorer II (REX II)A ROV/AUV Hybrid	AUV Lab	By REX II we enabled to remotely access live video and sensor data. It was only possible due to hybrid ROV/AUV	2009	http://auvlab.mit.edu/vehicles/#rex2
12.	Monterey Ocean Observing System (MOOS) Upper Canyon Experiment	MBARI Lab	Data collected from underwater sensors transmitted to surface buoy. This experiment suggested and practically implemented that data can be further transmitted via satellite communication and charging of this surface buoy is done via solar system	2010	http://www.mbari.org/moos/mooring/mooring.htm

Table 2 (continued)

S. no.	Projects/experiments UWSN	Research Lab	Objectives of project	1991–2001	URL
13.	Submarine Volcanism Project	MBARI Lab	This is having the goal to better understand the volcanic processes in the deep sea environment	2010	http://www.mbari.org/volcanism/
14.	Autonomous Ocean Sampling Network (AOSN)	MBARI Lab	It comes up with advanced ocean models in new robotic vehicles	2011	http://www.mbari.org/aosn/
15.	Midwater Time Series	MBARI Lab	This team used the time-series data to monitor bio-diversity and gauge the responses of the animals in the oxygen minimum zone	2011	http://www.mbari.org/rd/projects/2011/midwater.htm
16.	CLIDCS (component level intelligent distributed control systems)	Florida Atlantic Univ.	Due to underwater environment corrosion and fouling can happen very soon. Protection of a node and marine material from Sea water corrosion is going to developed under this system	2012	http://www.ome.fau.edu/research
17.	Unified nonlinear control systems for AUV	Florida Atlantic Univ.	Once AUV launched, it becomes difficult to control due to dense environment and various others underwater factors. Challenge of AUV's controlling is going to tackle via this project	2012	http://www.ome.fau.edu/research
18.	Nano-Composites	Florida Atlantic Univ.	Its goal is to disperse nanoscale reinforcement into structural polymers and produce components for structural applications	2012	http://www.ome.fau.edu/nano-composites-laboratory
19.	AUV-based BOSS sonar systems	Florida Atlantic Univ.	A sonar system named BOSS is going to develop under this project which will be based on AUV	2012	http://www.ome.fau.edu/seatech-the-institute-for-ocean-systems-engineering

Table 2 (continued)

S. no.	Projects/experiments UWSN	Research Lab	Objectives of project	1991–2001	URL
20.	Air-deployable underwater modem communication	Florida Atlantic Univ.	Up to now a buoy is only deployed over the sea-surface with antennas for broadcasting. Now a buoy below the water surface to be deployed under this project, beside the challenge of how to provide charging to that buoy for longer time	2012	http://www.ome.fau.edu/seatech-the-institute-for-ocean-systems-engineering
21.	NEREUS/Odyssey II A self-contained underwater mass-spectrometer system	AUV Lab	Designed to operate either independently on a mooring or winch line for pollution monitoring as well as for fundamental earth systems research	2008	http://auvlab.mit.edu/vehicles/#o2a
22.	Underwater acoustic communication	Acoustic Research Laboratory	It is a laboratory work where the research is not only limited to AUV's. It is also consists of acoustic signal strength to transfer data	2012	http://arl.nus.edu.sg/twiki/bin/view/ARL/Research

9 Simulation Analysis

In this paper the simulation results are conducted to analyze the performance of various techniques using AquaSim pack of NS-2 simulator ns-allinone-2.30. In this pack for UWSN, UnderwaterMAC as MAC layer protocol, UnderwaterPropagation as propagation type, UnderwaterChannel for underwater traversing are used to identify the link breakage and notify the same to network layer. Here Constant Bit Rate (CBR) is used as simulated traffic with traffic rate of 50 Kbps and the OmniDirectional Antenna type. These properties differentiate the UWSN simulation from WSN.

9.1 Performance Metrics

We evaluate performance of the protocol according to the following parameters:

Average Packet Delivery Ratio It is the ratio of the number of packets received successfully to the total number of packets transmitted. It reflects the efficiency and reliability of the network.

Average Delay It is the average time taken by a data packet for moving from source to destination. It involves detection and recovery delays. It is measured in seconds.

Energy Consumption It is the energy grasped by the nodes during data transmission. It is expressed as the average energy consumption of all the nodes in the network during the simulation.

9.2 Simulation Parameters

In the simulation, because of memory usage and running time of the code, time taken is 50 s. But there will not be much deviation in the results, as we chosen larger time intervals also. The experimental area size considered here is 1000×1000 m^2. Other simulation parameters are summarized in Table 3 for this scenario.

Table 3 Simulation parameters

Parameter	Value
Network size	50 nodes
Range	100 m
Initial energy	1000 J
Traffic rate	50 Kbps
Channel capacity	2 Mbps
Transmission power	2.0 W
Receiving power	0.75 W
Idle power	0.008 W
Filters	Gradient filter
Frequency	25 kHz
Packet size	50, 100, 150, 200, 250 bytes

9.3 Simulation Results

In UWSN each node has to send the data to the sink directly or indirectly. In some cases, node transmits its own data to the sink whereas in other cases, the technique of data aggregation is applied due to which the transmitted data is collected at a particular node and then transmitted to the sink. To validate the UWSN approaches and its results we have compared the simulation results of some techniques in underwater scenario. The techniques that are considered for evaluation are UCFIA [54], MARPCP [55], E^2DTS [56], ROSS [57], MCCCP [58]. The simulation results of the above mentioned techniques are presented graphically in this section.

The above represented graph in Fig. 5 shows the average packet delivery ratio for UCFIA, MARPCP, E^2DTS, and ROSS techniques. The data delivery ratio of ROSS scheme is better than other techniques w.r.t. increasing packet size.

The above represented graph in Fig. 6 shows the average packet delay for UCFIA, MARPCP, E^2DTS, ROSS, and MCCCP techniques. The delay of MCCCP scheme is much more than other techniques w.r.t. increasing packet size.

The above represented graph in Fig. 7 shows the average energy consumption during simulation for UCFIA, MARPCP, E^2DTS, ROSS, and MCCCP techniques. The energy consumed by UCFIA scheme is very less in comparison to other techniques w.r.t. increasing packet size.

10 Identified Areas of Research

Underwater Communication network being an emergent field requires vast research efforts in upcoming years. The technology has proven its beneficial existence in various underwater fields and future research is required to make it useful in other fields like maritime industry [59–72, 79, 80].

A. *Open Research Issues on Physical Layer* With respect to physical layer further study is required to develop energy efficient communication network

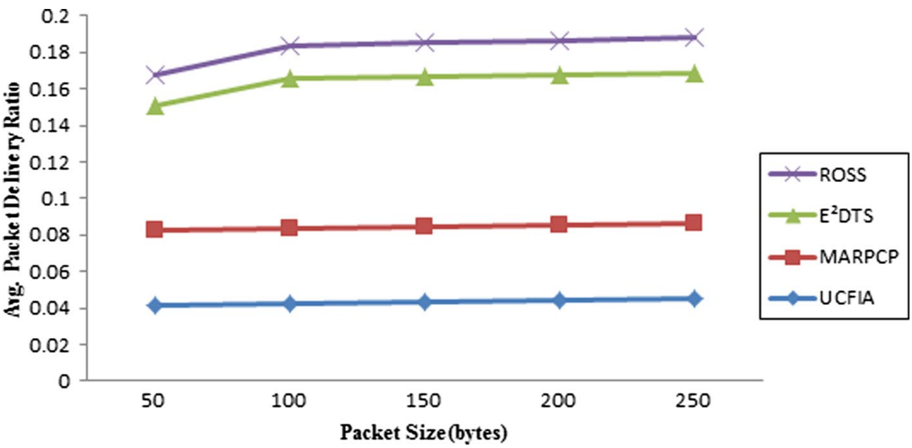


Fig. 5 Packet delivery ratio comparison of various techniques w.r.t. increasing packet size

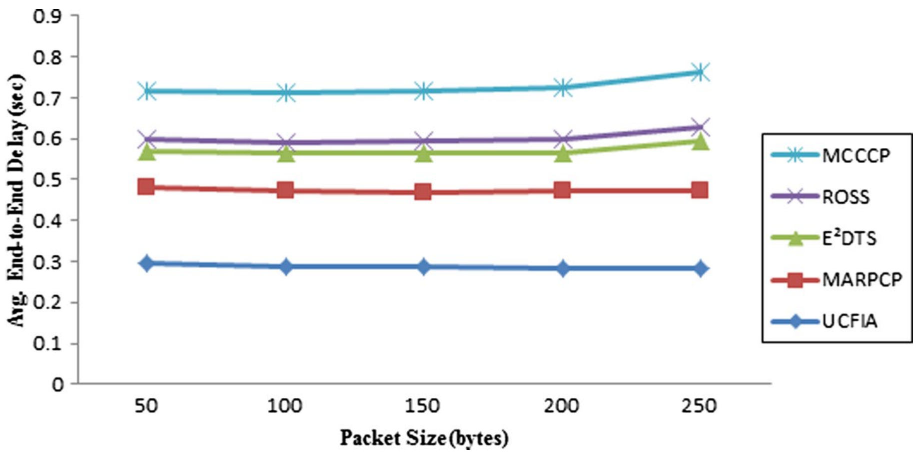


Fig. 6 Packet delay comparison of various techniques w.r.t. increasing packet size

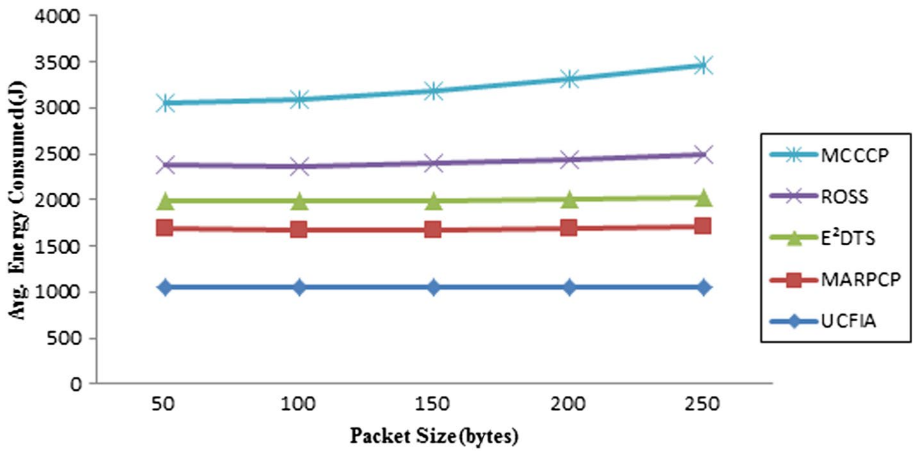


Fig. 7 Energy consumption comparison of various techniques w.r.t. increasing packet size

1. Research is required to form acoustic modems consuming low power and is energy efficient, that must be able to minimize the error rates by using FEC coders and maximize the bandwidth, are required to be developed.
2. Develop such a technique for sensors to avoid fouling and corrosion of these so that they can monitor and sense correctly for a long time.
3. In order to get better signal strength, work is required on modem, so that signals not get faded or dispersed to reach before destination.

B. *Open Research Issues on MAC Layer* Since MAC layer is a sensitive part in underwater communication, and today a lot of work related to this is going on.

1. Distributed CDMA-based schemes seem to be right choice for underwater communication by keeping in mind to lower the energy consumption rate.

2. Development of such protocols is required that limits the processing power consumed during FEC functionalities.
3. It is required to design protocol that can reduce the interference among users by having low cross-correlation and high auto-correlation properties
4. To enhance the efficiency of channel utilization, it is required to have the protocols with optimal data packet length.
5. Future work is required to form protocols support longer network lifetime, better way energy consumption, data delivery efficiency, bandwidth efficiency and longer stability by avoiding overhead of routing table maintenance.

C. *Open Research Issues on Network Layer* If we talk about routing protocols, this is the most important part for UWSNs. Design factors mainly affect them like node mobility pattern, network topology used, and energy consumption.

1. There is a need to develop mechanism for delay-insensitive applications to handle loss of connectivity. The research efforts are required to form protocols and algorithms to deal with unforeseen mobility of nodes, battery drain up, and failures.
2. Enhancement is required to develop algorithms for delay-sensitive applications like voice or video streaming.
3. Noticeably, to better utilize available resources and to perform fast adaption, it is required to have cross layer interaction among the layers
4. Accurate network modeling is necessary, so realistic simulation models or tools required to be developed.
5. Localization is a severe problem for acoustic communication.
6. Work is required to develop low-complex underwater communication technique with least energy expenditure.

D. *Open Research Issues on Transport Layer* The following issues must be studied in order to develop new effective reliable protocol for transport layer.

1. To tackle the feedback messages by destination node flow control approaches needs to be developed.
2. To obtain the cause of packet losses that it is due to congestion or high bit error rate or any other bad signal performance of acoustic channel, new strategies for UWSNs need to be developed.
3. Based on event model new event features transport protocol is desired to be developed.
4. It is necessary to maximize the network throughput efficiency, minimize congestion, maximum transport reliability. Optimal update policies are required for this.
5. It is important to track loss of connectivity so that the mechanisms may be devised to efficiently use the delay-tolerant applications.

E. *Open Research Issues on Application Layer* This layer is open to do research work for providing interface to all the applications being developed.

1. To the best of our knowledge network management protocol is desired to act as intermediate when communicate with lower layers.
2. A language code is required to communicate, give instruction, and take response in specified form with complete network as a whole.

11 Conclusion

Around 96% of the total global water is in the form of oceans, seas etc. It has always been challenging for the researchers to develop network or techniques to analyze the data of such extensive underwater environment. However UWSN has been designed with special features to collect, convert and store the enormous data found under the water. UWSN has emerged as an interesting field for research in quest of performing similar to terrestrial WSN in aquatic medium being a difficult environment. In comparison to electromagnetic or radio waves that are used in land based WSN, the UWSN works in acoustic waves which has its own limitations. There are several open challenges in UWSN required to be explored like the development of energy efficient routing techniques, limited battery depletion, and available bandwidth. These challenges are necessary to be resolved for efficient and reliable data transportation in various applications like assisted navigation, pollutants monitoring, mine detection, offshore exploration, disaster management, tactical surveillance. Here in this paper we have presented the communication architecture of UWSN to explain the working of the network. Further existing QoS, energy efficiency, fault tolerance issues are also discussed. The main stress is given to present an overview on the past research work in the field of UWSN on layer by layer basis as well as to analyze the unexplored issues as future scope or challenges that can motivate the scholars and the researchers to explore the area of UWSN. Undoubtedly, the technologies based on UWSN have proven their stand in various underwater monitoring and surveillance applications. However the continued or upcoming research may establish its benefits in timely detection of intruding AUVs like foreign submarines thereby preventing underwater attacks. It can also be used in preventing underwater disasters like Tsunami etc. by analyzing and informing the movements of tectonic plates under water.

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Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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