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Review

Review of Underwater Mobile Sensor Network for ocean phenomena monitoring

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ABSTRACT

Underwater Mobile Sensor Network (UWMSN) has marked a new era in ocean observation systems involving large scale ocean phenomena monitoring applications. These spatial and temporally varying applications demand multiple mobile entities for the collection of large amounts of data. This paper gives a concise view of the current state of the art of such networks comprising multiple Autonomous Underwater Vehicles (AUVs) and their challenges. It provides a literature review of the channel model and networking protocols of the physical layer, data link layer and network layer. Important algorithms and techniques for localization and time synchronization have also been reviewed. These algorithms play a huge role in a cooperative mission involving multiple AUVs, to achieve a common notion of time and to share the location information among the vehicles. Moreover, this paper includes a survey of various software platforms that support UWMSN, testbeds/real-time deployments of UWMSN developed by various research institutes/organizations and briefly discusses the recent advancement in the field of UWMSN.

1. Introduction

The much evolving ocean phenomena are compelling the researchers to progress in the field of ocean monitoring systems. There is a greater advancement in the field of underwater monitoring technologies that relied on smaller micromechanical sensor nodes deployed underwater which are stand-alone in nature, to a large number of sensor nodes forming a network called Underwater Sensor Network (UWSN) (Heidemann et al., 2012). But, these networks when deployed for any UWSN application may face severe challenges in a dynamic underwater environment. Though acoustic communication is preferred for underwater communication there are still many challenges faced by these networks due to the limited bandwidth, high and variable end-to-end delay, shadow zones, high bit error rate and high packet loss (Schneider, 2013; Cherkaoui et al., 2011). These characteristics of underwater communication are impairing the design and development of UWSN networking solutions. Due to these reasons, the network suffers from more reliable data collection and UWSN is very prone to energy depletion due to frequent retransmissions of packets caused by the link failures. Thus affecting the network connectivity. These challenges can be addressed by introducing mobility in UWSN (Coutinho and Boukerche, 2018).

A network formed by underwater mobile entities such as Autonomous Underwater Vehicles (AUVs) along with three-dimensional static UWSN or simply forming a network of multiple vehicles with similar or variable capabilities is a better solution for the aforementioned challenges. This network is termed as Underwater Mobile Sensor Network (UWMSN). The inclusion of the mobile entity/AUVs can be used as a bridge between the nodes to establish connectivity among faulty UWSN nodes, or it can be used to achieve faster data collection from the nodes of UWSN, else it may be helpful in the localization of nodes in UWSN and so on. These networks can be used in various applications such as oceanographic data collection, bathymetric surveys, military applications and so on (Felemban et al., 2015). Fig. 1 shows an illustration of UWMSN, where mobile nodes and static nodes are communicating among themselves and further sending the data to the sink node.

There are myriads of phenomena happening underwater, like some micro-level processes, eddies or coastal up-welling, tsunamis, plumes to global climate changes etc. These can be better studied with the advancement in the ocean observations systems. Fig. 2 shows the spatial and temporal variation of these ocean phenomena. From this figure, it is obvious that these ocean phenomena can even span in the range of centimetres lasting only a few seconds to those extending to thousands of kilometres and lasting for hundreds of years (Babin et al., 2008; Harrison, 2021).

Applications are often classified as time-critical and non-time-critical applications. Various applications require the exploration of the ocean at different depths. These applications make use of vehicles with

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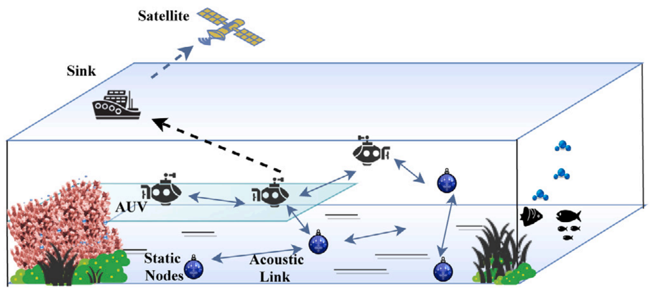


Fig. 1. An illustration of Underwater Mobile Sensor Network.

different capabilities such as huge and complex AUVs to small, micro AUVs, self-propelled vehicles like gliders, Remotely Operated Vehicles (ROVs), Autonomous Surface Vehicles(ASVs) and so on. The micro AUVs like MONSUN (Renner and Golkowski, 2016), Bluefin SandShark micro AUV (Monroy-Anieva et al., 2018), buoyancy controlled floats like μFloat (Underwood and Murphy, 2017) works in shallow water and supports short-range communication while AUVs like REMUS (Allen et al., 2006) and Sentry (Pontbriand et al., 2015) can go to greater depths and have a higher level of data collection ability and offers long-range communication. The networks of these AUVs are designed either to be centralized or distributed based on the requirements.

This literature focuses on a large-scale oceanographic feature tracking of underwater plumes using UWMSN. Ocean plumes are complex and evolving processes that could make a greater impact on ocean ecology. Various types of plumes considered here are (a) Hydrothermal vent plumes (Camilli et al., 2010), (b) Oil spills (Mazumder and Saha, 2006), and (c) Harmful Algal Blooms (HABs) (Ryan et al., 2014).

(a) Hydrothermal vent plume: It occurs at the ocean floor. When water seeps into the earth's crust due to a chemical reaction it gets heated up and ejected back to the ocean. This chemical fluid rises and spreads horizontally in the cold water forming hydrothermal vent plumes. This non-buoyant layer spreads from tens to thousands of kilometres (Camilli et al., 2010; Cannell et al., 2006). These vents are detected by tracking their chemical and physical signature back to their source and are usually found by examining temperature anomaly, particle content, water velocity, chemical traces of iron, manganese, helium, methane, and hydrogen sulphide.

(b) Oil spills: These are formed due to natural or manmade causes. When an event of spill happens, it rises to the surface forming a slick and falling out over time. The spatial extent of the plume depends on the source from which it occurs. For example, the plume formed due to the leaking of the MC252 Macondo well site in the Gulf of Mexico lasted for five days and spread over 30 km. Depending on the source this lasts for hours to days. The occurrence of oil spills is found by the presence of hydrocarbons in the ocean water (Mazumder and Saha, 2006; Gilabert et al., 2015; Kumar et al., 2020).

(c) HABs: They are devoid of a particular source. Prosperity in nutrients and minerals in water triggers the growth of algae which spreads from tens to thousands of kilometres having a vertical spread in the range of centimetres. Their presence is determined by either in situ monitoring or determined in labs (Robbins et al., 2006; Dabrowski et al., 2016). Plumes vary in physical, chemical and biological properties. These dynamic features extend from tens to thousands of metres horizontally and can be found at any depth throughout the water column and are temporally varying. So to create a synoptic data set of these dynamic features proper samples should be collected and processed. Various approaches are available in the literature for sampling the plumes (Petillo and Schmidt, 2012; Farrell et al., 2005; Das et al., 2010; Jakuba et al., 2005; Petillo et al., 2010; Bayat et al., 2017). Some of the methods adopted for plume monitoring are finding the source of the plume, detecting the boundaries, or covering the entire area of the plume (Li et al., 2006; Burian et al., 1996; Kemna et al., 2017; Chen et al., 2012). AUVs with different capabilities are used according to the nature of the plume.

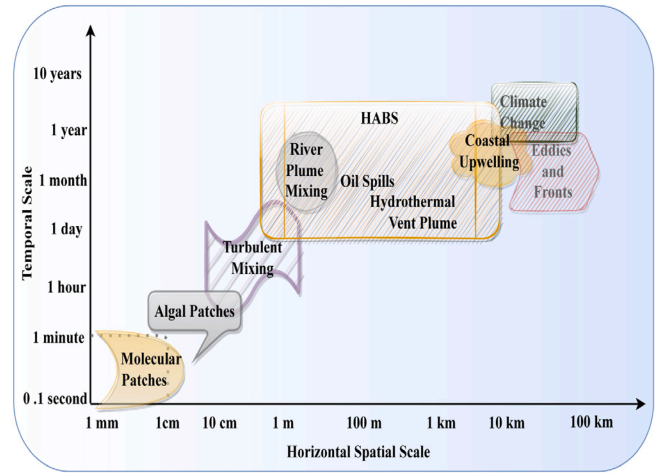


Fig. 2. Spatial and temporal variations of ocean phenomena (Babin et al., 2008; Harrison, 2021).

Tracking the plume with a single AUV faces challenges due to Spatio-temporal aliasing, where it is difficult for a single AUV to collect data on different places at different times (Petillo et al., 2011). This necessitates the use of multiple AUVs for sampling the evolving ocean phenomena. The problem is much similar to the multi-robot exploration in terrestrial networks, where the load is shared among multiple vehicles (Khalifeh et al., 2019; Ho et al., 2019). This paves a way for using a network of AUVs distributed over space and time and thus avoiding the aliasing problems in the data set. The other advantages of using multiple AUVs are a reduction in the mission cost by reducing the operation/logistic cost and overall coverage time.

The organization of the paper is as follows. Section 2 describes the challenges faced by the network of AUVs and the channel model for underwater acoustic communication. Network protocols for AUV fleets are discussed in Section 3. A detailed review of protocols in the physical layer, data link layer and network layer is covered here. Section 4 provides the review of localization and time synchronization in UWMSN. Further, Section 5 speaks about some of the prominent works carried out so far in UWMSN. Recent advancement has been presented in Section 6. And finally Section 7 concludes the paper.

2. Challenges faced by the network of underwater Autonomous Vehicles

The recent advances in underwater technologies has paved the development of different networking strategies with AUVs. However, there are many challenges faced by them. Some of them are as follows:-

(1) Unstructured Environment:- The environment underwater is more complex than any of its counterparts on the land and surface. Due to the dynamic and unstructured environment, navigation and obstacle avoidance using underwater vehicles are challenging. The exploration of an unknown environment with varying water current and turbidity possesses greater risk, while considering the case of multiple AUVs communicating with each other in a certain topology (Schneider, 2013; Cherkaoui et al., 2011). However, due to the dynamic nature of underwater environments, there are higher chances for the static or mobile nodes to drift from their initial position causing changes in their topology. This arises the need to address the effects of mobility.

While addressing the mobility, one has to deal with the voluntary and involuntary movements caused to the nodes in the network. For instance, the UWSN is innately mobile due to the highly dynamic nature of the underwater environment that often drifts the nodes in the order of 2 to 3 knots (Shantaram et al., 2005). Whereas, the voluntarily drift is made by the mobile nodes/AUVs for accomplishing a mission. There are various factors like network connectivity, coverage, and localization of nodes that are linked with the performance of any protocols in a network. These metrics are however prone to the changes due to the mobility of nodes. This creates a very need to study those defined metrics using realistic mobility models. Some of the mobility models are explained below.

(a) Mobility models for involuntary mobility:- The meandering Current Mobility model (MCM) is one of the most realistic mobility models proposed in Caruso et al. (2008) to capture the effects of nodes movement with ocean currents. In this model, sensors are moved by the effect of meandering sub-surface currents and vortices. This model can be used in a large coastal environment. The nodes are initially deployed in a small area and they will assume their corresponding positions thereafter by moving in accordance with the mobility model. This scenario is more realistic for underwater mobile sensor networks applications, especially in monitoring the dynamics of the oceans. But this applies only to a two dimensional surface. Therefore, in Mandal et al. (2017) a physical mobility model, named Oceanic Forces Mobility Model (OFMM) for a 3D space, is introduced. This model was developed by incorporating all the oceanic forces imparted on the nodes. While the work carried out in Bouabdallah (2019) presents a realistic mobility model, considering the physical movement of randomly scattered and freely floating sensor nodes under ocean currents. The time evolution of the network in terms of coverage and connectivity was further analysed here, using the networking communication protocols such as routing, localization, and medium access.

(b) Mobility models for voluntary mobility:- The voluntary movement of mobile nodes/AUVs deals with the individual motion behaviours of the nodes employed for specific mission purposes. For an effective simulation of a mobile network, it is of atmost importance to use a mobility model which could greatly mimic the movement of real-world mobile nodes. This helps to determine the efficacy of a protocol in a given scenario. Usually, these models are classified into entity mobility models and group mobility models. The random walk mobility model is one of the most commonly used entity models. In this model, the nodes assume to have independent motion. The nodes can randomly choose the destination and a velocity to head towards the destination. While in the group mobility models, the behaviour of all the nodes in the network is considered. Here, the nodes are collectively moved from one reference point to another (Kalkan, 2011).

A bio-inspired search algorithm for AUV is described in Ma (2014). A random walk mobility model is employed as a motion model to search for the parameters to navigate. This represents an animal moving towards the goal performing a random search same as that of the random walk model. Although, these models are easy to implement they tend to be unrealistic in real-world scenarios. Considering the case of a swarm of AUVs employed for a search mission these models cannot be implemented directly. Therefore in Tholen and Nolle (2017) an adapted random walk model is introduced. While dealing with the classical random walk mobility model the new position is randomly chosen from a defined neighbourhood, i.e, a random step size for the AUV has been chosen. But this is practically not a feasible solution while dealing with AUVs, as the different step sizes will lead the AUVs to accelerate and decelerate instantaneously increasing the energy consumption and thus decreasing the operation time. Apart from the ideal case where the velocity of AUVs is kept constant while the heading is changed iteratively. But in the case of adopted random walk, the velocity of the AUV is limited thus keeping the maximum step size limited. The AUVs are driving at their maximum speed during the entire search and a heading of AUV is chosen randomly. Whereas, the work considered in Danielis et al. (2021) considers a movement logic provided by built-in INET models (INET Core Team, 2021). The INET models provide various mobility models such as linear motion, random waypoint motion etc. These models can also be combined to achieve more complex motion. This work focus on finding the metrics that are greatly defined by the movements of thrusters in AUVs. But it does not consider a realistic model that considers the oceanic forces of the ocean environment.

However, while dealing with the AUVs an effective way to describe the mobility system is to rely on the kinematic constraints of the AUVs. In order to set up a mobility model for AUVs, the kinematic constraints of the real device have to be considered and have to set up a feasible path between two or more points. A generic mobility model described in the simulator would only consider a cartesian coordinate system with three coordinates. But in the case of AUVs, it has to consider not only the actual node position but also the heading direction.

A mobility model for Remus, Typhoon AUVs and gliders is introduced in the work carried out in Franchi et al. (2017), after getting inspired by the mobility model introduced by the Andreo Saco in summer codes (Andrea Sacco, 2010). Andreo Saco describes the waypoint mobility models for Remus and glider AUVs using constant velocity and fails to address other the kinematic constraints for the AUV. But the current model describes the movements between two points, by finding out more intermediate points with realistic kinematic constraints of the AUVs using the waypoint mobility model.

(2) Unavailability of Satellite-Based Navigation or GPS:- GPS is the widely available technique used for navigation and positioning. But cannot be used underwater, as GPS is based on radio frequency and it cannot penetrate the seawater after a certain range. A very-low-frequency range of 3–30 kHz can travel through the seawater but for a shorter distance not more than 20 m. Therefore positioning and navigation of AUVs is a big challenge and often relies on acoustic-based techniques (Paull et al., 2013; Bahr et al., 2009). Various techniques like LBL and USBL techniques are used for the positioning of single AUVs. Cooperative localization is utilized especially for search and survey missions with a team of vehicles. This is done with the aid of a vehicle fitted with USBL at the ocean surface for geo-referencing and enabling the communication among the team members to pass the location information among themselves using an acoustic modem. This is more elaborately explained in Section 4.

(3) Underwater Acoustic Communication:- Underwater communication is mainly established using acoustic, radio or optical waves. Due to the properties of seawater, the RF waves get greatly attenuated underwater and require higher transmission power and larger antennas. This can be used for short-range communication up to 10 m. However, researchers show the use of RF in Schill and Zimmer (2007). The use of RF enables communication in a swarm of small AUVs operate very closely with each other. Optical waves on the other hand provide high data rates (in the order of Gbits/s) but get easily scattered underwater and can only be used for short-range communication. Acoustic waves are preferred over the others as it travels a relatively large distance without much absorption (Syed et al., 2006). However, there are many challenges faced by acoustic communication underwater such as:-

(i) Latency:- Sound waves travel five orders of magnitude slower than the speed of light. Sound travels at a speed of 1500 m/s creating larger propagation delays and can lead to relatively large motion-induced Doppler effects.

(ii) Limited Bandwidth:- Because of multi-path and Doppler spread the underwater acoustic channel is spatially and temporally varying. Thus limiting the available bandwidth and making it dependent on both the range and frequency. Short-range systems that operate over several tens of metres may have more than 100 kHz of bandwidth, while long-range systems that operate over several tens of kilometres may have bandwidths of only a few kHz.

(iii) High bit error rate:- Probability of bit error rate is a very large and temporary loss of connectivity (shadow zone) sometimes occurs, due to the extreme characteristics of the channel. Underwater acoustic communication, therefore, has only low bit rates of the order of tens of kilobits per second. Underwater links are classified based on their range as very long, long, medium, short and very short (Syed et al.,

2006). And their links are further classified into vertical and horizontal based on the direction of the sound ray for the ocean bottom. The link characteristics may vary due to multipath spreads, time dispersion and delay variance. Based on the depth, the ocean water is mainly classified into shallow water and deep water. Usually, the shallow water spans up to 200 m from the surface. Beyond 200 m it is considered as deep water. Section 2.1 describes the channel model for UW acoustic communication (Akyildiz et al., 2005; Lanbo et al., 2008; Domingo, 2008; Stojanovic, 2007; Dhongdi et al., 2017).

2.1. Channel model of underwater acoustic communication

For designing a physical layer, parameters such as (i) frequency of operation, (ii) modulation technique, (iii) data rate, and (iv) power level of source has to be specified. Calculation of the Signal to Noise Ratio (SNR) is of paramount importance in the physical layer design. For determining SNR, a passive equation of SONAR (Sound Navigation and Ranging) (Heidemann et al., 2012) can be utilized. According to this equation, SNR at the receiver side can be obtained as follows:

$$\mathrm{SNR} = \mathrm{SL} - \mathrm{TL} - \mathrm{NL} - \mathrm{DI} \tag{1}$$

where SL is source level of transmitter, TL is transmission loss, NL is the ambient noise level in ocean and DI is directivity index. DI is usually set to zero value. In underwater acoustic domain, these values are expressed in dB re μPa, where the reference value of 1 μPa amount to 0.67×10^{-18} W/m^2. The level of the received signal at the receiver is obtained by using the equation of Received Level (RL) as follows:

$$\mathrm{RL} = \mathrm{SL} - \mathrm{TL} \tag{2}$$

where RL is expressed in dB as,

$$\mathrm{RL} = 10 \log \frac{\text{received intensity}}{\text{reference intensity}} \tag{3}$$

Reference intensity in underwater acoustic is taken as 0.67×10^{-18} W/m^2.

In a similar way, Source Level (SL) is expressed in dB as,

$$\mathrm{SL} = 10 \log \frac{\text{transmission power intensity}}{\text{reference intensity}} \tag{4}$$

where transmission power intensity (I_t) at 1 m distance from the source is expressed in terms of transmission power P_t (Watt) as,

$$\mathrm{I}_t = \frac{\mathrm{P}_t}{4\pi \times 1m} \tag{5}$$

Source Level can be expressed in terms of radiated source power P_t (at 1 m distance from the source) directly as,

$$\mathrm{SL} = 10 \log \left(\frac{10^{12} \rho c P_t}{4\pi} \right) \tag{6}$$

where $\rho = 1000$ Kg/m^2 is water density and c is speed of sound in water.

For a receiver with narrow band B around operating frequency f, the SNR is expressed as,

$$\mathrm{SNR} = \mathrm{SL} - \mathrm{TL} - \mathrm{NL} - 10 \log \mathrm{B} \tag{7}$$

(1) Transmission Loss:- Transmission Loss (TL) is a sonar parameter defined as the accumulated decrease in acoustic intensity when an acoustic pressure wave propagates outwards from a source.

$$\text{Transmission Loss}(r, f, T, D) = k\ 10\ log\ r + \alpha_t\ (f, D, T) \times r\ \times 10^{-3} \tag{8}$$

The first term in (8), represents the spreading loss, and the second term represents the absorption loss. Here, k is the spreading factor, and α_t is the absorption coefficient with unit dB/km, r is the range in metres, f is the frequency of operation in kHz, D is depth in metres, T is the temperature of water in degree celsius. The spreading factor k accounts for geometrical spreading, which refers to the spreading of sound energy as a result of the expansion of the wavefronts. There are two types of geometrical spreading: spherical (k = 2), characterizing the deepwater communication, and cylindrical (k = 1), characterizing a shallow water communication.

The absorption coefficient can be expressed empirically, using Thorp's formula (Brekhovskikh and Lysanov, 1991) which gives α_t in dB/km for frequency f in kHz as follows:

$$\alpha_t = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f} + (2.75 \times 10^{-4}) f^2 + 0.003 \tag{9}$$

This formula is generally valid for frequencies above a few hundred Hz. For lower frequencies, the following formula can be used:

$$\alpha_t = 0.002 + 0.11 \frac{f^2}{1+f^2} + 0.011 f^2 \tag{10}$$

Thorp's formula provides an approximation of TL as a function of frequency (depth is not considered here). More accurate results can be obtained by considering the various important mechanisms of sound attenuation in the ocean such as viscous absorption and ionic relaxation. Several different formulas are available in literature for calculating absorption coefficient α_t such as Fisher and Simmons (1977), Francois and Garrison (1982a,b), Schulkin and Marsh (1963) and Ainslie and McColm (1998). These equations have comparable accuracy as well as computational requirements. For illustration purposes, Francois and Garrison's equation has been used in this paper for the calculation of TL. In Francois and Garrison (1982b), authors have provided the equation for calculating sound absorption in water depending on acoustic frequency, pressure, acidity, temperature and salinity. This equation is valid for the frequency range of 100 Hz to 1 MHz. Here, total absorption is calculated as the summation of three terms (1) contribution of boric acid, (2) contribution of magnesium sulphate and (3) contribution to absorption by pure water component.

For the acoustic frequency f in kHz, the absorption coefficient α_t can be calculated in dB/km as follows:

$$\alpha_t = \frac{A_1 P_1 f_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \tag{11}$$

The first term in (11) represents the contribution to absorption by boric acid, second term represents the contribution by magnesium sulphate and third term refers to contribution due to pure water. Terms A_1, A_2 and A_3 boric acid, magnesium sulphate and pure water component respectively (in dB km^{-1} kHz^{-1}). f_1, f_2 and f_3 represent the relaxation frequency for boric acid, magnesium sulphate and pure water (in kHz). P_1, P_2 and P_3 represent the depth pressure for boric acid, magnesium sulphate and pure water respectively.

From equations it is found that TL increases with an increase in operating frequency as well as with the increase in communication range (or distance). This is the peculiar property of underwater acoustic communication which limits the useable bandwidth. It is also inferred that TL increases with increasing range but decreases with the increase in depth.

(2) Noise:- There are many factors that constitute noise in the ocean environment. Four sources like turbulence, shipping, waves, and thermal noise are taken to model the ambient noise in the ocean. Most of the ambient noise sources are described by Gaussian statistics and a continuous power spectral density (p.s.d.). The following empirical formula gives the p.s.d. of the four noise components in dB re μPa per Hz as a function of frequency in kHz (Coates, 1990).

$$10\ \log\ N_t(f) = 17 - 30\ \log f \tag{12}$$

$$10\ \log\ N_{sh}(f) = 40 + 20\,(sh - 0.5) + 26\ \log\ f - 60\ \log\,(f + 0.03) \tag{13}$$

$$10\ \log\ N_w(f) = 50 + 7.5 w^{1/2} + 20\ \log\ f - 40\ \log\,(f + 0.4) \tag{14}$$

$$10\ \log\ N_{th}(f)\ =\ -15\ +\ 20\ \log\ f \tag{15}$$

where N_t is the noise due to turbulence, N_{sh} is the noise due to shipping, N_w is the noise due to wind, and N_{th} represents the thermal noise, f is the frequency in kHz. Turbulence noise influences only the very low-frequency region ($f < 10$ Hz). Noise caused by distant shipping is dominant in the frequency region 10 Hz–100 Hz, and it is modelled through the shipping activity factor sh, whose value ranges between 0 and 1 for low and high activity, respectively (Stojanovic and Beaujean, 2016). Surface motion, caused by wind-driven waves (w is the wind speed in m/s) is the major factor contributing to the noise in the frequency region 100 Hz–100 kHz (which is the operating region used by the majority of acoustic systems). Finally, thermal noise becomes dominant for $f > 100$ kHz.

The overall noise power spectral density for a given frequency f is then:

$$N(f) = N_t(f) + N_{sh}(f) + N_w(f) + N_{th}(f) \tag{16}$$

(3) Self Noise:- In addition to the ambient noise, the self-noise caused by the vehicle itself should also be considered. The noise can make an impact on the hydrophones which are mounted on the AUVs. The noise will affect the hydrophones if water passes over them or through the mechanical structures mounted on them. The self-noise depends on the location at which the transducer is mounted and its directivity (Havelock et al., 2008). The self-noise's impact is similar to the isotropic noise spectrum obtained in World War II, performed on the submarines (Jiang, 2008). The self-noise is decreased with an increase in ambient noise but is severely affected when the vehicles move slowly or stationary (Kinsler et al., 1982).

(4) High Delay and Delay Variance:- Speed of sound in water is four times faster than the speed of sound in the air but is five orders of magnitude smaller than the speed of light. The slow speed of sound affects the performance of communication systems and the design of the network protocol stack as well. Acoustic propagation speed depends on factors such as salinity, depth and temperature. The temperature of the ocean further depends on the weather, time of the day, environmental factors and depth. This temperature variability has a large impact on acoustic speed. Underwater acoustic propagation speed can be modelled using various formula from literature such as (i) Coppens formula (Coppens, 1981), (ii) Del Grosso equation (Del Grosso, 1974), (iii) UNESCO equation (Chen and Millero, 1977) or (iv) Mackenzie (Mackenzie, 1981).

A nine term equation of Mackenzie for calculation of sound speed in ocean is as follows:

$$\begin{aligned} c = 1448.96 + 4.591T - 5.304\times10^{-2}T^2 + \\ 2.374\times10^{-4}T^3 + 1.340(S-35) + \\ 1.630\times10^{-2}D + 1.675\times10^{-7}D^2 \\ -1.025\times10^{-2}T(S-35) - 7.139\times10^{-13}TD^3 \end{aligned} \tag{17}$$

A vertical profile of sound speed in seawater using the Mackenzie equation has been shown in Fig. 3(a). Here, Salinity is 35 ppt and surface temperature has varied from 16 °C to 20 °C. In Fig. 3(b), variation of sound speed has been shown for varying salinity. Here, surface temperature has been assumed as 18 °C and salinity has been varied from 30 to 40 ppt.

Based on temperature variations, ocean water can be divided into three layers. Water depth up to 200 m is the first layer. This layer is most variable because of wind mixing and daytime heating effects. This layer usually consists of two sublayers, the surface layer (from surface to around 100 m) and the seasonal thermocline layer (from 100 m to 200 m). Sound speed has a negative gradient in this layer (typically in the summer season) since the water at the surface is warmer than the water below. Sound speed decreases with depth in this layer. The second layer is the main (permanent) thermocline layer up to around 1000 m and is associated with minimum sound speed. Sound speed decreases primarily because of a decrease in temperature. Below this layer, from 1000 m till the ocean floor is the third layer termed as a deep isothermal layer. The temperature in this layer is almost constant. The linear increase in sound speed in this layer is mainly because of an increase in depth giving rise to a positive speed gradient.

Sound speed in ocean water is highly variable depending upon factors such as temperature, salinity and depth. The usual range of sound speed under various operating conditions is from 1450 m/s to 1550 m/s. In literature, an average value of 1500 m/s is considered for simplicity. This slow speed results in a large and variable propagation delay (0.67 s/km) and reduces the throughput of the system considerably.

(5) Multipath:- An acoustic signal can travel via multiple paths from the transmitter to the receiver. In the case of shallow water communication, sound propagates by repeated reflections from sea-surface and sea-floor, causing multipath propagation. Signal suffers higher attenuation because of these reflections, based on frequency, incident angle, and sediment type (Domingo, 2008). In the case of deep water, surface and floor reflections can be neglected if the transmitter and receiver are not located near the sea surface or floor. However, the spatially varying sound speed can create wave refractions leading to a significant multipath effect in deep water. A channel impulse response of a multipath channel is given by the following equation,

$$h(\tau,t) = \sum_{i=1}^{P} \gamma_i(t)\exp(j\theta_i(t))\delta(\tau-\tau_i(t)) \tag{18}$$

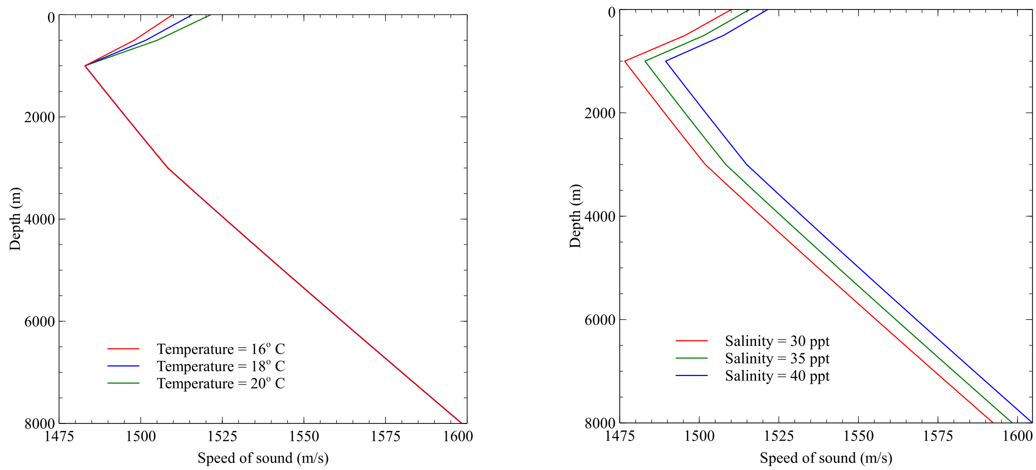
wherein P is the number of multiple paths, γ_i and θ_i is the amplitude and phase of the signal arrived by ith path, and τ_i is the time-delay of the ith path.

For very short-range AUV operations, multipath will be affected by the range-depth ratio, which is expected to produce fewer multipath signals at the hydrophone from surface and seafloor reflections (Hajenko and Benson, 2010; Parrish et al., 2007). It has been found that some improvement can be gained through directing the beam of the transmitted signal and the directional properties of the receiver (Waite, 2002), however, this will require an additional level of complexity for mobile AUV due to the need for vehicle positioning before sending or when receiving a signal.

(6) Doppler spread :- The motion of the transmitter/receiver of AUVs contributes to changes in the underwater acoustic channel response. This occurs through the Doppler effect, which causes frequency shifting as well as additional frequency spreading. The magnitude of the Doppler effect is proportional to the ratio $a = \frac{v}{c}$ of the relative transmitter–receiver velocity to the speed of sound. Because the speed of sound is very low compared to the speed of electromagnetic waves, motion-induced Doppler distortion of an acoustic signal can be extreme (Jiang, 2008). For example, assuming the device velocity as v = 2 m/s, carrier frequency f = 30 kHz, and sound speed as c = 1500 m/s, Doppler shift frequency is $f_d = \frac{vf}{c} = 40$ Hz. If the symbol duration Sd = 0.1 ms, (or a data signal bandwidth of 1 kHz), then the normalized Doppler per symbol is $f_d S_d = 0.04$. This example shows that a large Doppler shift reduces the coherence time of the channel. It also indicates that in the case of mobile networks, channel variation needs to be accounted for on symbol to symbol basis.

3. Network protocols for AUV fleets

This section deals with networking protocols for a fleet of AUVs. Various technology-related issues in the design, analysis, implementation and testing of the network are also considered. This section deals with protocol development in physical, data link and network layers.



(a) A vertical profile of sound speed in seawater as the function of depth for varying surface temperature.

(b) A vertical profile of sound speed in seawater as the function of depth for varying salinity.

Fig. 3. Effect of sound speed vs. depth for varying temperature and salinity.

3.1. Physical layer

The underwater acoustic channels are highly dispersive making them vulnerable to Doppler spread caused by the mobility of dynamic underwater environments. Phase variations are frequent in shallow, long and medium-range channels making it extremely difficult for phase tracking. Incoherent modulation schemes like FSK (Frequency Shift Keying) have been used in the field of acoustic domains for the development of WHOI Micro-modem (Singh et al., 2009) and other commercial modems such as Teledyne-Benthos (Green, 2016) to ensures simple and robust communication, thus mitigating the effects of phase variations (Cabral, 2014).

The modulation techniques used in the underwater environment should be resilient to the multipath effects and Doppler spread. Incoherent modulation techniques like FSK with good error correction capability can counter the effects of multipath while coherent techniques like BPSK with an adaptive equalizer is a good solution to resolve Doppler spread. The probability of bit error rate plays a key role in determining the modulation technique. Below, we provide an insight into how the modulation technique is chosen based on the Bit Error Rate (BER).

- **Determining the probability of error for various modulation techniques:-**
  The probability of error for various modulation techniques determines the quality of acoustic links. We can have a look at how the probability of error is determined from the SNR. Short-range communication of 500 m between AUVs is chosen here. The SNR is calculated by using Eq. (7). From this equation, it is obvious that the SNR level is greatly affected by the transmission loss.
  Considering the operating frequency of 30 kHz, TL is determined for 500 m using Eq. (8). It is observed that TL is around 57 dB (max) at various depths with a communication range of 500 m. Noise level NL is also minimum at around 40 dB (considering w = 5 m/s and sh = 0.5).
  The SNR for various power levels are then found using Eq. (7) for 500 m, as shown in the Table 1. This table provides the values of SL for various power levels of transmission Pt in Watts. RL for the range of 500 m has been given in column 4. Column 5 gives the SNR for 500 m for the bandwidth of 10 kHz.
  The ratio of Eb (Energy per bit) to No (Noise power spectral density) for determining the probability of error can be obtained from chosen SNR as follows:

$$\frac{E_b}{N_o} = \left(10^{\frac{\mathrm{SNR(dB)}}{10}}\right)\frac{B_N}{R} \tag{19}$$

Table 1
SNR for various power levels for 500 m range.

Sr. No	P_t	SL	RL (dB) for a range of 500 m	SNR (dB) for a range of 500 m
1	1	170.77	113.77	33.77
2	10^{-1}	160.77	103.77	23.77
3	10^{-2}	150.77	93.77	13.77
4	10^{-3}	140.77	83.77	3.77

Table 2
Determining the bit error rate for different modulation scheme.

Sr. No.	Modulation scheme	Probability of bit error	500 m range
1	BFSK	$P_b = Q\sqrt{\frac{E_b}{N_o}}$	5.3×10^{-7}
2	BPSK	$P_b = Q\sqrt{\frac{2E_b}{N_o}}$	2.6×10^{-12}
3	QPSK	$P_b = Q\sqrt{\frac{2E_b}{N_o}}\left[1 - \frac{1}{2}Q\sqrt{\frac{2E_b}{N_o}}\right]$	2.6×10^{-12}
4	16-QAM	$P_b = \frac{3}{4}Q\sqrt{(\frac{4}{5})\frac{E_b}{N_o}}$	1.2×10^{-6}

where B_N = B is the noise bandwidth. Using Eq. (19), E_b/N_o value obtained for power level P_t = 0.01 W, B = 10 kHz at a distance of 500 m is 23.82. The data rate taken here is 10 kbps. It is inferred that with the increase in distance between the AUVs, the SNR decreases drastically. The results of various modulation techniques are tabulated in Table 2. It is observed from the mentioned table, the probability of bit error for BFSK and 16-QAM is higher as compared to BPSK and QPSK for both the ranges. QPSK scheme also gives approximately same performance of that of BPSK but has more stringent phase synchronization requirement. Now we can have a look at the various modulation techniques available in the literature. They are described below.

Multi-Frequency Shift Keying (MFSK) is the modulation scheme adopted for shallow water AUV swarm networks. Here, the distance between the vehicles range from 3–10's of metres. The transmission and data communication for a swarm of AUVs gives a better tradeoff between the bandwidth and efficiency by embedding an isotropic antenna operating at 300 kHz. Even though the frequency used is higher than the conventional network, it could suppress harmful multipath effects. M-FSK with M = 4, 8 and 16 is effective in suppressing the multipath effects and helps in low cost modem implementation (Tabacchiera et al., 2012).

Peer to peer communication protocol for AUV network has been explained in Smith et al. (1997). The protocol has been interfaced with the acoustic communication system of Ocean Explorer (OEX) AUVs. It uses the acoustic telemetry system's Multi-Frequency Shift-Keying (MFSK). It makes use of 56 frequencies for concurrent transmission of 24 bits. Each bit is represented by two frequencies for FSK signalling, thus requiring 48 frequencies. Four frequencies are meant for packet counting and parity along with another four unused frequencies reserved for the future. The effective use of time guards between the successive pulses in this modulation scheme helps to counter the multipath effects. But these schemes are not bandwidth-efficient and are restricted to low bit-rate applications.

The advancement in Digital Signal Processing (DSP) and the available coherent modulation schemes like PSK (Phase Shift Keying) and QAM (Quadrature Amplitude Modulation) lead to the development of long-range and high throughput systems. The work carried out in Freitag et al. (2000) speaks about coherent modulation schemes used in REMUS AUVs in Very Shallow Water (VSW), in a depth of 3–8 m with a range extending to 1–5 km and a data rate of 60–5000 bps. But the acoustic communication using AUVs in VSW is very challenging. The maximum range and data rate are determined by the propagation conditions. Based on the AUVs configuration and the type of mission, there exist a lot of communication requirements in the VSW communication network. The multi-rate functionality available in the system helps to improve the efficiency following the range, as there are variations in SNR at the receiver. This system supports phase-coherent signalling and various coding techniques. The high-rate signals are meant for applications with single-user while the low-rate signals support multi-user or the least SNR cases.

Considering the case of single-user modulation and reception, the two highest rate signals utilize QPSK and BPSK modulation and a concatenated error-correction coding method. The outer layer uses a high-rate Reed–Solomon code, while a block code is used for the inner layer and the data rate is varied by selecting different block codes. A multi-channel Decision-Feedback Equalizer (DFE) with a phase-locked loop is used as the receiver. The equalizer reduces the effect of multipath and retracts the carrier drift. To allow the DFE to take advantage of the gain from the inner block code, the receiver uses a delayed filter update.

Whereas in low-rate multi-user communications, signal uses Direct-Sequence Spread-Spectrum (DSSS) modulation. DSS communications utilize a family of k L-length codes which are transmitted at the chip rate of $R = l/Tc = B$, where B is the maximum bandwidth. The link rate is then B/L bits per second. The system uses 15-and 31-chip Gold codes.

Mine Counter Measure (MCM) operation in shallow water using REMUS AUVs is explained in Freitag et al. (2000). It enables the cooperative mission by communicating with an operator and multiple vehicles. WHOI has taken initiative to develop Micro-modems to get installed in the REMUS vehicles. The modem was at a size of 1.75 by 7.5 inch. In order to make it compatible with onboard acoustic navigation systems, the communication frequency has been increased. This results in an integrated system that needs a Micro-Modem DSP card with a size of 1.75 by 4.5 inches. The modulation scheme used here is Frequency-Shift Keying with Frequency-Hopping (FH-FSK). When simple and robust FSK gets combined with frequency hopping it can be used in shallow water environments having multipath effects. The data rate used here is 80 bps after applying the overhead from error correction techniques. It is designed to operate at 25 kHz and uses 4 kHz of bandwidth.

Later multirate PSK was incorporated, having a data rate of 300–5000 bps excluding the overhead and error correction. A floating-point coprocessor has been designed and implemented in the Micro-modems to enable the PSK receiver capability. Complex adaptive algorithms like DFE are needed for multirate PSK reception. The network designed here works as a master–slave network, where almost every data gathered by the vehicles get transmitted to the surface buoy with a high-rate receiver. A method to improve the reliability of the PSK by using multiple receiver channels is mentioned in Freitag et al. (2005). Multi-Channel input is introduced by incorporating another small card along with a DSP card and co-processor cards. The card has two banks having four channels, where the data flows from the analog to digital converter to the modem.

Orthogonal Frequency Division Multiplexing (OFDM) based communication is explained in Bereketli et al. (2017). This is an effective technique which could be used when a large portion of the bandwidth of the channel is taken by the noise. To overcome the effect of ISI, multi-carrier modulation is preferred over the single carrier modulation technique. Furthermore, OFDM is capable of dealing with interference and fading in a mobile network. A peer to peer communication of AUVs has been performed in shallow water, pond and sea experiments subjected to noise and Doppler spread. Since the OFDM is sensitive to Doppler effects and frequency offset due to the relative motion of the transmitter and the receiver, Doppler compensation is performed according to the autocorrelation using the cyclic prefix. BPSK and QPSK schemes along with Low-Density Parity Check (LDPC) coding are used to infer the error rate levels in all scenarios. It is found that the transmission scheme is capable of correcting all bit errors among nearly one million bits transmitted up to a distance of 1 km, yielding a payload rate of 15.6 kbps with 4096 subcarriers and QPSK modulation.

A scenario of high data rate deep water acoustic communication is described in Shimura et al. (2019). Marine-Earth Science and Technology in Japan (JAMSTEC) developed a manned submersible SHINKAI6500 and an AUV URASHIMA to operate for deep-sea research. These vehicles are equipped with acoustic communication systems to send commands (downlink), monitor or retrieve observed data (uplink) with the mother ship. The transmission data rates of an uplink communication in these systems are 16 kbps with QPSK at the range of 6500 m (2.0 bps/Hz) and 32 kbps with 16 QAM at the range of 3500 m (4.0 bps/Hz), respectively. The system is further updated using a prototype of a new high-rate uplink communication system adopting single-carrier modulation. An experiment to confirm its performance has been executed with a system fitted in SHINKAI6500. As a result, a data rate of 69.24 kbps with 128 QAM using the frequency band from 15 to 25 kHz has been achieved in the dive at the depth of 3600 m, that is, the spectral efficiency is 6.924 bps/Hz.

3.2. Data link layer

Here, we focus on mobile networks that could collaborate for sensing, data acquisition, and exchanging information for mission completion. These nodes should communicate among themselves in a cooperative mission where the data exchange is indispensable. For instance, nodes need to get the location information for localization as well as navigation. In network operations, nodes may require neighbour locations to avoid vehicle collisions, to build a map of the survey area, or to simply act as relays in between the nodes. For this effective channel, utilization is paramount.

The MAC layer of the data link layer allows the effective utilization of a shared channel by the multiple nodes in a network. However, due to the challenges of a dynamic underwater environment, the design of the MAC protocol demands more attention than its terrestrial counterpart. In mobile underwater networks, in addition to the innate challenges like limited bandwidth, large propagation delay, high bit error rates, loss of connectivity and multipath effects, mobility should also be considered. This demands the need for developing MAC protocols that could adapt to spatially and temporally varying channels and their resulting dynamic topologies (Diamant and Lampe, 2010; Molins and Stojanovic, 2006). MAC protocols should therefore consider the following parameters in the design process, such as energy efficiency, scalability, network throughput, fairness, latency, and bandwidth utilization (Zenia et al., 2016). The efficiency of MAC protocol lies in ensuring energy saving by collision avoidance mechanism, high network throughput and low channel access delay.

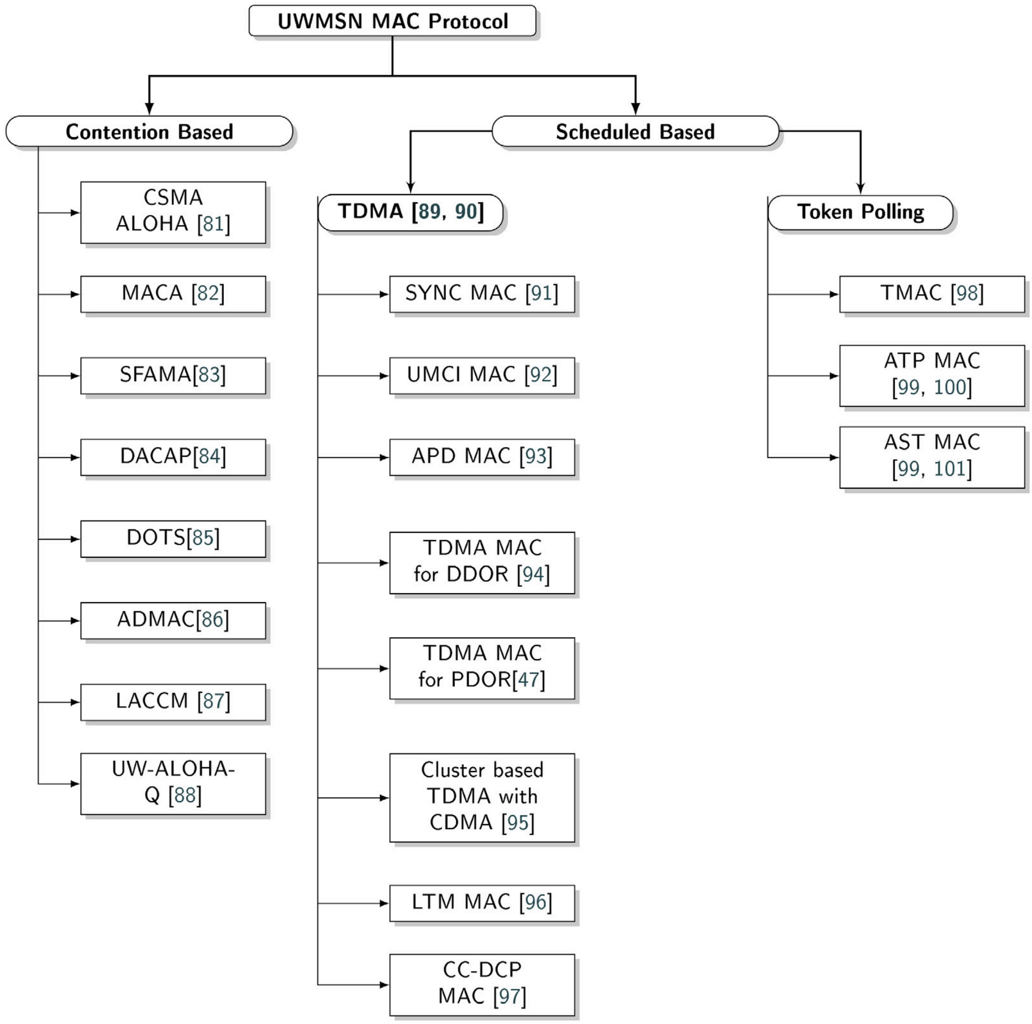


Fig. 4. Classification of MAC protocols for UWMSN.

This literature covers the MAC protocols for mobile UWMSN. They are classified here into two. Contention based and Scheduled based, the scheduled based is further divided into TDMA (Time Division Multiple Access), and Polling based as shown in Fig. 4.

1. Contention Based MAC Protocols

Contention based MAC is proposed using a scenario of Cooperative Target Detection (CTD) in Guerra et al. (2010). Two scenarios are explained here as shown in Figs. 5 and 6. Performance evaluation of two test cases is performed and accessed. The first case supports the communication of an AUV to static nodes moored in the sea bed. The data exchange takes place between the AUV and sensor nodes and vice versa. While the second case focused on a mobile network. In this scenario, there are two computationally efficient AUVs (whose positions are deterministic). These AUVs are placed on the two edges (say a plane) and are 10 km apart. In order to enable communication between them, mobile relay nodes of lesser capabilities like mini AUVs are placed between them. The nodes are free to communicate in either direction.

The performance of the given scenarios has been accessed, based on the bifurcated contention-based protocol, i.e. random access and handshake mechanisms. In random access protocol, CSMA ALOHA protocol is chosen while Distance Aware Collision Avoidance Protocol (DACAP) is used for handshake mechanism. The following paragraph explains the advancement from CSMA ALOHA to DACAP protocol (Petrioli et al., 2008).

In CSMA ALOHA the channel is sensed before the node starts its transmission (Kleinrock and Tobagi, 1975). The node will sense the channel and back off, if a transmission is taking place, and starts after a random interval of time. However, this is more vulnerable in terms of packet collisions. Therefore in MACA (Karn et al., 1990) (Multiple Access for Collision Avoidance), a handshake mechanism is introduced using the control packets called RTS and CTS (Ready To Send and Clear To Send).

However this appears not to be a solution in situations where the distances among nodes are not proportional. Researchers have tried to mitigate the effects of collision by introducing carrier sense in MACA in Fullmer and Garcia-Luna-Aceves (1995). And this protocol is named as Floor Acquisition Multiple Access protocol (FAMA). Control packet length constraints have been introduced to avoid collisions due to the multiple concurrent transmission in a variable underwater environment. Therefore, Slotted FAMA (SFAMA) is introduced in a dynamic network of AUVs in Molins and Stojanovic (2006).

In SFAMA, multiple concurrent transmission is prevented by the time slotting mechanism, where a node could send data only at the beginning of the time slot. This eliminates the choice of the longer control packets. The handshake mechanism described in Distance-Aware Collision Avoidance Protocol (DACAP) proposed in Peleato and Stojanovic (2007) reduces the frequency of packet collision based on minimizing the average handshake duration, by allowing a node to use different handshake lengths for different receivers. The protocol takes advantage of the receiver's tolerance to interference when the two nodes are closer

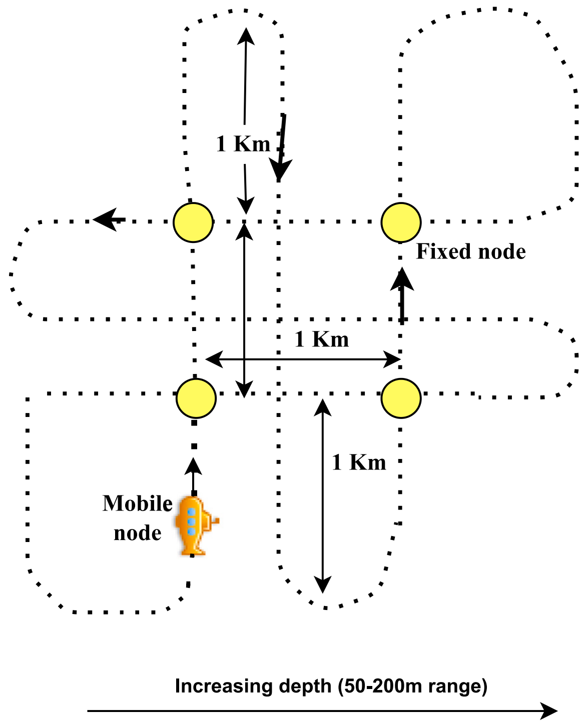


Fig. 5. Scenario 1: 4 fixed, bottom mounted nodes and 1 AUV patrolling the area following a closed-loop trajectory.

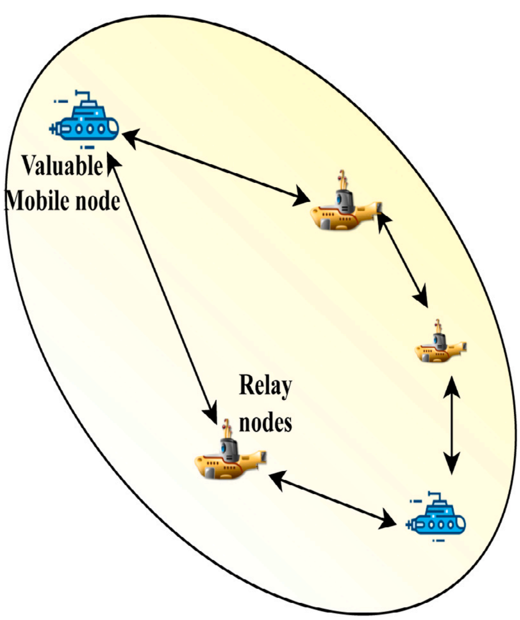


Fig. 6. Scenario 2: a fully mobile network with two external, more valuable nodes communicating through a network of cheaper mobile nodes in between.

than the maximal transmission range. DACAP is found to give a better throughput than the SFAMA.

Longer propagation delay in an underwater environment is utilized in the Delay-Aware Opportunistic Transmission Scheduling (DOTS) protocol proposed in Noh et al. (2014). The protocol makes use of the longer propagation delay in an underwater environment for concurrent transmissions of multiple packets. The protocol uses passively obtained local information like neighbouring nodes' propagation delay map and their expected transmission schedules to increase the chances of concurrent transmissions while reducing the likelihood of collisions. The nodes build their local propagation delay maps by overhearing packets, but the schedule gets outdated if there is a continuous movement of nodes. However, guard time is used herein schedules to cope with node mobility. The channel reservation is done via handshaking and the nodes are time synchronized.

A strategy to increase the transmission throughput has been proposed in Adaptive Directional Communication MAC protocol (AD MAC) (Lu et al., 2011) using the directional antennas. The nodes select the transmission strategies to send the RTS and CTS packets omnidirectionally or directionally.

A traffic-aware protocol named as Load Adaptive CSMA/CA MAC (LACCM) is proposed in Zhang et al. (2018). This is mainly designed for a single-hop network where one or more AUVs are communicating with the static sensor node. This is a handshake based protocol using RTS and CTS packets. In heavy load traffic with a single handshake, the node sends two data packets to reduce the overhead due to the control packets. This uses a carrier sense mechanism as well. If the channel is sensed busy, a binary back-off algorithm is used which reduces the achievable channel utilization.

The idea of reinforcement learning in slotted ALOHA protocol is introduced in Park et al. (2019). The Reinforcement Learning Based MAC protocol (UW-ALOHA-Q) for mobile networks provides more effective adaptation to the time-varying environmental conditions to improve the level of performance (e.g. in terms of channel utilization). Superior channel utilization performance can be potentially achieved concerning the alternative state of the art protocols owing to the minimal signalling overheads and absence of inefficient handshaking procedures.

UWMSN requires up-to-date data rather than larger packet size data or data packet trains. For dense AUV networks, the network configuration is greatly interconnected. Network traffic is continuous and relatively heavy in such a network. Therefore, it is advisable to use scheduled based MAC protocols that support the regular packet generation and data exchanges. However, a scheduled based protocol needs time synchronization and it has limited scalability and flexibility in a mobile network. Scheduled based MAC protocols are described in the next subsection.

2. Scheduled Based MAC Protocols

Scheduled based MAC protocols are usually based on FDMA, TDMA and CDMA protocols, where the available bandwidth is partitioned to schedule multiple users. Polling and Token ring protocols are also under the schedule based categorization. One of the greater advantages of this category is that it reduces packet collisions.

In a channel where the bandwidth is relatively low, further dividing it into frequency sub-bands will lead to frequency fading, as the subchannel UW bandwidth is lesser than the coherence bandwidth of the channel. Thus FDMA remains a non-worthy choice for the requirement.

OFDMA (Orthogonal Frequency Division Multiple Access) on the other hand, combined with a contention-based protocol in a network of AUVs is proposed in Daladier and Labrador (2009). A MAC protocol called 2MAC is introduced in the MAC sub-layer to improve the throughput of the network by using the multi-channel capabilities of OFDM at the physical layer. However, this results only in three subchannels because of the smaller bandwidth.

CDMA (Code Division Multiple Access) is another technique (Salva-Garau and Stojanovic, 2003), which can provide some resilience to the multipath propagation and frequency fading. But for a larger network, it is difficult to assign pseudo code for each node. Even if a code reuse strategy is adopted like the frequency reuse concept, it requires more complex receivers.

While in TDMA, time is divided into slots and individual nodes are assigned for a particular slot and this is most common in scheduled based protocol. TDMA based MAC protocols have several advantages in terms of simplicity, fairness and energy efficiency. Collisions, idle listening and over-hearing can be avoided in these protocols. The hidden node problem is easily solved without using extra message overhead because neighbouring nodes transmit at different time slots. There are also certain disadvantages associated with TDMA based MAC protocols such as poor channel utilization, scalability on a dynamic basis and the requirement for time synchronization. Therefore, this literature focuses mainly on the scheduled based protocol based on TDMA and polling based protocol which is a hybrid version of both scheduled based and contention-based techniques. They are explained below, in two subsections.

(a) TDMA Based Protocols

A TDMA based MAC used for a cooperative mission for mapping the ocean bottom is explained in Stojanovic et al. (2002). This requires frequent communication among the AUV groups. The objective of the multi AUV mission is to build a map for an area spreading across several square kilometres. Each vehicle uses the navigational and sensor information from other vehicles to build the map. Each vehicle has to do localization based on the information shared among them. A matrix carrying the information about intravehicular distance, Doppler frequency shift, relative speed and location is maintained in each vehicle. This information is communicated to other vehicles using a standard TDMA MAC protocol.

Each vehicle has allotted an individual slot in each time frame, where the corresponding vehicle broadcasts the matrix and the others will listen and update their matrix. A guard band has been set at the end of each time slot. It is based on the maximum propagation delay. This ensures the successful reception of data packets without collision. Due to the larger guard bands used in this conventional TDMA, it can only be used for a smaller size AUV network.

However, the larger guard bands in conventional TDMA protocols can be effectively utilized by incorporating the concepts of spatial reuse (Diamant and Lampe, 2010). The concurrent transmissions are entertained, given no collisions are occurring at the receivers and at the same time considering the possible interference from neighbour nodes (Liu et al., 2021).

A method to overcome the Spatio-temporal variability in the underwater link has been given in Ma and Lou (2011). This can be achieved by using Spatio Temporal Graphs (ST-G). These graphs calculate the weightage of the Spatio-temporal link and send the data to the member nodes. Based on the available information, the nodes schedule their transmission.

Another scenario similar to the plume monitoring is described in Caiti et al. (2012a). A group of AUVs are assigned to find a High-Value Asset (HVA). The search domain spans around (800×800) m and HVA in a region of (500×500) m. There are about 4 to 9 AUVs that have to be moved towards the HVA performing two subtasks. The first task is to move towards the asset and the second one is to move away from the closest neighbours but have to stay in the communication range with at least one of its neighbours.

The AUVs traverse such that they cover a maximum area around the HVA minimizing the overlap of sonar detection range and meanwhile safeguarding their communication links with the neighbours. The only information that the AUVs have to share among themselves is their position data and sonar range. Here, the nodes are aware of their location at all times. There are two communication schemes used here. The first one uses CSMA MAC, where the nodes can sense the busy channel in order to prevent packet collisions. They back off for a certain duration before transmission. As the AUV cannot autonomously sense the collisions, it has to send ACK after successful reception of data creating additional overheads. The nodes cannot broadcast the messages instead have to send them individually using multi-hop routing.

In the second method, TDMA MAC has been used where each node transmits at its scheduled intervals. Here, the nodes are broadcasting the message and no addressing system is implemented at the receiver. A more complex scenario that uses TDMA along with routing and addressing systems has also been implemented. The CSMA technique shows poor performance in terms of latency and collision avoidance than TDMA. The pure TDMA is having relatively smaller latency when compared to TDMA with routing and address implementation. But it gives the same efficiency in the case of packet collision.

Various TDMA MAC protocols applied on centralized networks are explained in Yun et al. (2011), Centelles et al. (2020) and Cho et al. (2018). A TDMA MAC called sync MAC is introduced in Yun et al. (2011). It is implemented in a centralized network, where the sink or a buoy at the surface takes control of the communication process. The communication is only initiated between the AUV and the sink node individually based on the TDMA schedule.

The Underwater Multirobot Cooperative Intervention MAC protocol (UMCI-MAC) is proposed in Centelles et al. (2020). The protocol aims to minimize the delay and jitter to ensure effective communication among a group of AUVs in underwater cooperative interventions. The protocol uses a TDMA strategy. One AUV assumes to be a master and sends commands to the rest of the AUVs (slaves) for coordinating the communication process. The process happens in two phases named as control and data phase.

In the control phases, the master node transmits a sync packet to initialize the communication. Here, the nodes receive the sync packet based on their relative distance from the master. This process is termed as initial synchronization. After receiving the sync packet, the AUVs will get to know the schedule at which it has to send a control (CTRL) packet.

The slot duration allotted by the master node to the respective slaves is the time taken to transmit the CTRL packet plus the maximum propagation time. Whereas, in the data phase the master node will send a CTS packet to the corresponding AUVs and they can send their data to the master node.

An Asymmetric Propagation Delay MAC (APD-TDMA) is proposed in Cho et al. (2018), where the collisions at the sink node are avoided by deferring data transmission after the reception of a beacon packet from the sink node. The node has to wait for a certain duration after the reception of a beacon packet determined by the estimate of propagation delay over two cycles. The future location of AUVs is estimated using the data packet arrival times. The protocol is appropriate for networks consisting of nodes with constant velocity.

TDMA MAC for distributed network is proposed in Schill et al. (2006) and Schill and Zimmer (2007).

A protocol that makes use of a cross-layer functionality combining the network and MAC protocol is explained in Schill et al. (2006). The author proposes a DDOR (Distributed Dynamical Omnicast Routing) routing protocol for a large network of AUVs. This is a distributed algorithm adapted to omnicast communication. Here, a dense network is addressed which makes use of RF communication as the distance between the nodes is relatively less.

A reservation-based TDMA is used in the medium access layer. In an assigned time slot, each vehicle can at first send a longer message that includes its local schedule and the payload data followed by a very short two-byte request slot for scheduling an upcoming time slot. The major advantage is that it provides localization and schedule information to other vehicles. However, the high interconnectivity of nodes results in larger schedules which causes high end-to-end delay.

An improved version of the DDOR is explained in Schill and Zimmer (2007). Pruning of the local schedules for efficient swarm communication is explained in Pruned Distributed Omnicast Routing (PDOR). In PDOR, geographic/radiometric collision models over the topological model are considered. Due to the strong attenuation of radio waves over the distance, there exist only a small region probable for collisions. This gives the freedom to reissue the slots of a distant node to a much closer node — thus allowing spatial reuse.

PDOR differs from the DDOR mainly in two aspects. The first one is that the collisions in PDOR are resolved based on the signal strength instead of node index and every node differ in their signal strength from their corresponding neighbours. In DDOR, the decision to occupy a slot is coherent to two-hop neighbours of a particular node. While in PDOR, the decision is more localized. The nodes which are geometrically closer to a particular node will assign a slot to the node, while the other nodes within the range or at a 2-hop neighbourhood assign the same slot to other nodes that have greater signal strength. This shrinks the virtual neighbourhood of nodes in dense areas.

The modification takes into account the nodes that are in the final schedules, those are already used to mark as booked slots. A slot is marked "O" (for its own use) only if at least one neighbour in the local schedule confirms the slot. The second difference lies in the request mechanism. The nodes apply for empty slots within the schedule. If empty slots are not available node asks for a blocked slot. If no blocked slots are available, nodes request the slot occupied by nodes with the lowest locally measured signal strength. Thus PDOR implements spatial reuse by pruning the schedules.

It is observed that the schedule length was found to reduce from 64 slots to 16 slots in a 40-node network, giving a smaller frame size compared to DDOR. The protocol also achieves a shorter End-to-End packet delay. Thus, PDOR modifies both the TDMA frame length and slot allocation to improve the TDMA performance.

A Cluster-based TDMA with CDMA protocol is proposed in Salva-Garau and Stojanovic (2003). This combines TDMA and CDMA protocols. This is a clustering-based scheme that is scalable and supports the spatial reuse of channel resources. The cluster is formed by the mobile entities where the in-cluster communication is achieved through TDMA, and adjacent clusters use the CDMA technique.

MAC protocols for a heterogeneous network is proposed in Mao et al. (2016) and Hollinger et al. (2011). A Location-based TDMA MAC (LTM-MAC) for single-hop networks with AUVs is described in Mao et al. (2016). This work focuses on a network with several static nodes and one or two AUVs. In LTM-MAC, the static nodes listen for a sufficiently long time before their transmission in order to consider a situation where an AUV needs to establish communication. If the AUV has data to send, it will occupy the time slot and other static nodes postpone their transmission thus ensuring the timely access of AUVs.

Communication Constrained Data Collection Problem (CC-DCP) is discussed in Hollinger et al. (2011), and it adopts the strategy of a TDMA MAC protocol to inform path planning methods for AUV. Path planning is done to minimize the travel time and to maximize the gathered information. CC-DCP is applied to gather information from sensors through a noisy channel modelled probabilistically. The protocol considers only the data gathered by the AUVs and does not take into consideration any urgent orders issued by the AUV.

(b) Polling Based Protocols

Polling is another categorization under schedule based protocols. Polling based approach uses a token to indicate when a node has finished its transmission or when to begin its transmission. It relies on the arrival of a token to trigger the transmission of the next node in the schedule instead of fixed schedules like TDMA.

Token-based Medium Access Control protocol (TMAC) (Egbo et al., 2009) is used in a fleet of AUVs. A virtual token is used here, but it is not passed between the vehicles. Instead, it is maintained within each vehicle based on the transmitted and received messages. A fixed time of thirty seconds is maintained for 5 AUVs in the fixed TDMA time schedule. The virtual tokens act as a mechanism to trigger vehicles to transmit in their time slots. This avoids the need for time synchronization among the vehicles in the TDMA protocol.

The token in each vehicle gets updated when it transmits or receives the messages. The message includes the expected vehicle ID and expected time, the next message should arrive from a transmitting vehicle; or the time to send its message if the vehicle ID matches the token identification number in its memory. If messages are dropped, token updates are done on a time-out basis, so that the cycle is not broken.

An Adaptive Token Polling MAC (ATP-MAC) and Adaptive Space-Time TDMA (AST-TDMA) is proposed in Burrowes (2014), Burrowes and Khan (2009) and Burrowes et al. (2013). ATP-MAC is for a non-time critical mission. This is mainly meant for surveying or monitoring applications that are suitable for vehicle configuration that maintains a structured formation pattern. This work depicts a bus topology with a coordinator vehicle. The ATP-MAC proposed in Burrowes (2014) and Burrowes and Khan (2009) uses a token polling ring approach. This allows the slot size to be adaptive depending on the transmission and propagation time between the consecutive vehicles.

AST-TDMA (Burrowes, 2014; Burrowes et al., 2013) on the other hand is used for time-critical missions like rescue and search missions. It is used in a distributed network for applications such as searching hydrothermal vents. The vehicles move as a cluster in which individual vehicles move in a random fashion, based on the trajectory calculation done by each vehicle from the localization information obtained from neighbouring vehicles. Regular communication is indispensable for the vehicles for the mission. A TDMA based approach and a token similar to that of ATP-MAC facilitate an adaptive slot size to efficiently accommodate the long propagation delays used for the implementation. In the next subsection network layer protocol is discussed.

The next subsection talks about the network layer protocols and their further classification in UWMSN.

3.3. Network layer protocol

In applications involving long term cooperative missions, the design and development of the routing protocol is of prime importance. Network layer plays a key role in routing the packet from the source to destination. Designing a suitable routing protocol for a mobile underwater sensor network is however challenging due to its innate characteristics (Ahmed et al., 2017; Ayaz et al., 2011). It may also experience "shadow zones" which cause high bit error rate and temporary loss in connectivity due to harsh underwater environments (Schneider, 2013).

The sparse deployment of underwater sensor nodes (both mobile and static) due to high cost stands as a challenge for fully connected networks. Above all, the nodes (despite being static or mobile) may undergo random movement due to strong currents paving the way for partial or no connectivity. Therefore, while designing the routing protocol one should consider the frequent link breakages, end-to-end delay and a fair packet delivery ratio in a highly dynamic environment. This literature focuses on various routing protocols used for collaborative missions and they are broadly classified into four categories (1) on-demand based, (2) delay-tolerant based, (3) location-based, and (4) AUV aided network for data collection. The classification and examples of each category are shown in Fig. 7.

Proactive routing protocols apart from reactive/on-demand routing protocol incurs larger overhead in a network where topology changes are frequent (Ghoreyshi et al., 2017; Domingo and Prior, 2008). This leads to the updating and sharing of routes among the nodes in every topology update. Thus, it becomes unsuitable for a dynamic underwater network. Whereas, in an on-demand routing protocol, routes are created only on demand and support the dynamics of the network (Nicolaou et al., 2007; Tong et al., 2016).

While dealing with the fleet of AUV networks there exist fair chances for the vehicles to move away from the communication range of each other. Based on the application requirement, the network can be designed as intermittently connected networks where the loss of connections are frequent. In the case of on-demand based routing, it is always necessary to have a route established before the packets are delivered. While in a Delay Tolerant Network (DTN), the connectivity needs to get established only when two vehicles come in the transmission range of each other (Hossen and Rahim, 2015).

In location-based routing protocols, the position of the nodes/their geographic coordinates are necessary for the routing information and remains as a suitable routing technique in an underwater network.

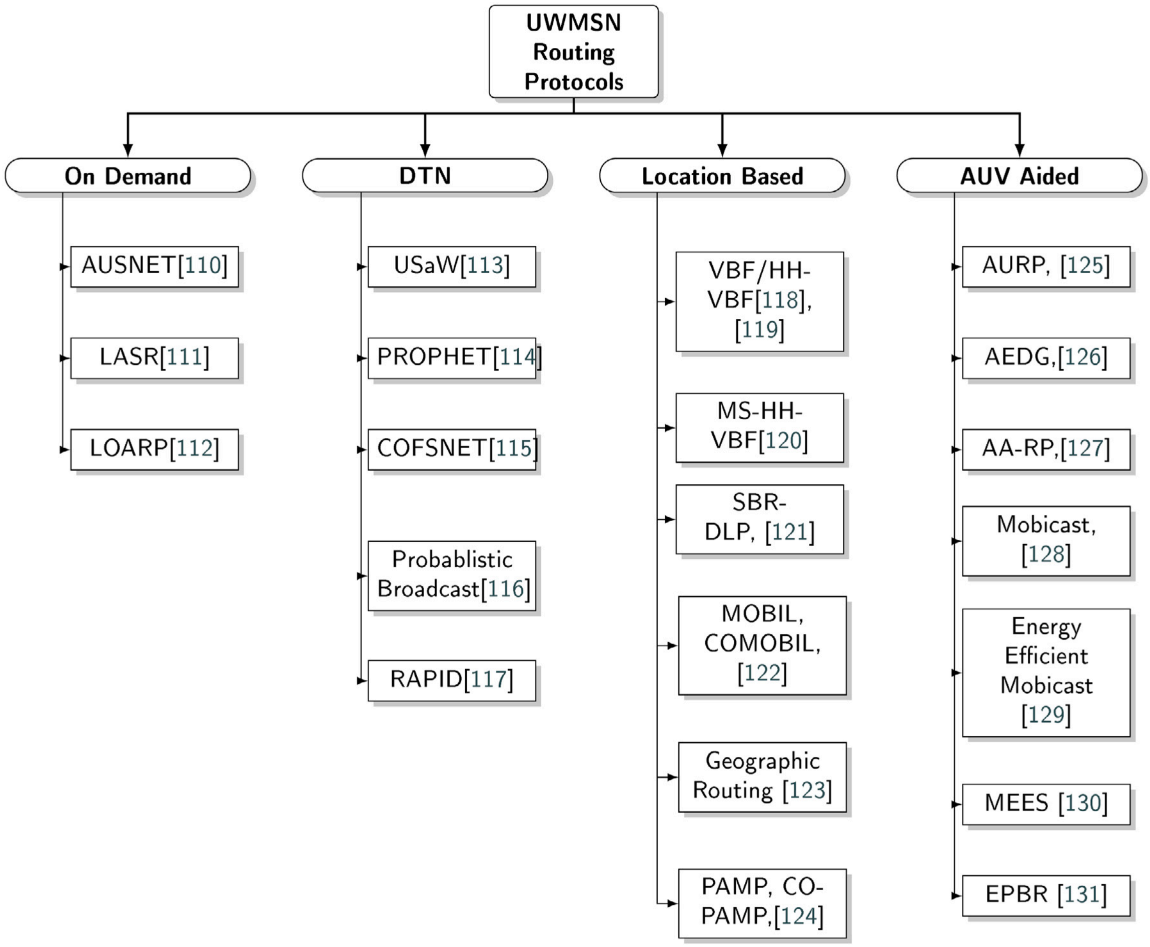


Fig. 7. Classification of routing protocols in UWMSN.

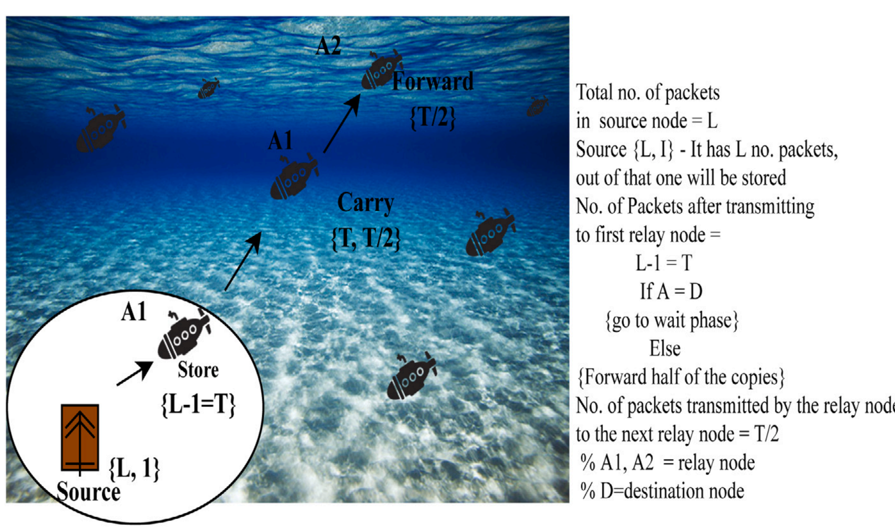


Fig. 8. Routing in Underwater Spray and Wait Protocol.

It has lesser signalling overhead, though it requires accurate location information (Chirdchoo et al., 2009).

There is another category named AUV aided data collection where the AUVs are used for data collection from the nodes which are adhered to the ocean floor. Here AUVs act as either relay nodes or mobile sinks to gather data from the static sensor network (Cheng and Li, 2017). In the following paragraphs, a detailed explanation and examples of each category are provided.

1. On-Demand Routing Protocol

An example of an on-demand routing protocol is the Autonomous Undersea Systems Network (AUSNET) (Benton et al., 2004). Here, a network is employed for cooperative missions. A fleet of AUVs are deployed as a cluster and they assume a line formation to engage in a cooperative search mission. AUSNET has been developed as an extended version of Dynamic Source Routing (DSR) used in mobile ad-hoc networks.

In this work, DSR (Johnson et al., 2007) is modified for a low bandwidth underwater environment. DSR gives the network the freedom of self-formation as well as self-maintenance through the process of route discovery and route maintenance. AUSNET also allows the nodes to learn the network routes on demand and listen to the node discoveries from their neighbours. The nodes can act as routers and allow scalability of the network by the addition or deletion of a particular node based on the requirement. Thus the network emerges as self-healing in an ad-hoc topology.

In order to take the advantage of undersea communication, AUSNET put forward the idea of Prediction Based Routing (PBR), where it is assumed that the movement of underwater vehicles are not random and are predictable even if not known before. This process evolves under a fair utilization of available vehicle movement information and makes an estimate of the current network topology. This is done based on the vehicle trajectory by using the dead-reckoning technique. The topology is determined with the aid of a spanning tree algorithm, and the shortest path to the destination can be found while reducing the considerable overhead created in the DSR protocol. In case the prediction fails, AUSNET falls back on DSR's route discovery mechanism.

LASR (Location Aware Source Routing) is another protocol tailored from DSR for undersea AUV networks (Carlson et al., 2006). This protocol imbibed two techniques to compensate for the delay in the underwater network. The first one is by introducing location awareness, considering the implicit information from the incoming transmissions, to develop an estimate of local network topology. While the second one is to use a link quality metric to replace the simple hop count metric used by the DSR.

The local topology built in this protocol is based on the relative locations of the neighbour nodes using a tracking system. It uses the range information estimated from time-of-flight measurements on incoming transmissions. While DSR relies on the minimum hop count route metric as the best path and it may not always be true but LASR consider the best route based on the link quality. However, this requires a low drift clock for time synchronization. Both LASR and AUSNET are applicable for networks with smaller topology changes and not for one with a larger number of nodes.

LOARP (Low Overhead Routing Protocol)is a routing protocol used for both static and mobile networks (Rahman et al., 2013). This is a low overhead on-demand routing protocol consisting of two phases:- route discovery and route maintenance. In the route Discovery phase, the routes are created on-demand. The route maintenance phase deals with the recovery of failed routes and this incurs a lot of routing traffic. However, this protocol tried to minimize the routing traffic effectively either by monitoring the network data traffic or by creating lazy acknowledgements if necessary. With the reduction in network traffic, the packet collision decreases leading to a higher packet delivery ratio.

2. Delay Tolerant Networks

The motive of delay tolerant networks is to establish communication in a network that suffers from intermittent connectivity or in a network, where an end to end route between the nodes is not found (Guo et al., 2010; Rahman and Frater, 2015). This makes use of the mobility of nodes, to ensure the communication via store and carry forward approaches for data propagation. Based on the number of copies of the data packet/replica, the DTN is mainly classified into forwarding based and replication-based. In forwarding based, the messages are forwarded without replication and a copy of the packet is maintained in the network. While in replication-based, the packets are replicated from the source node and routed to the intermediate relay nodes to ensure successful delivery to the destination (Varma et al., 2019).

The approach of the store and carry forward has been applied in Underwater Spray and Wait (USaW) protocol described in Varma et al. (2019). The network is designed such that, there are static nodes adhered to the seafloor to act as source nodes and a network of AUVs as intermediate relay nodes to route the data disseminated from the source node to the destination (sink) at the water surface. Here, the source node replicates the data and keeps only a single copy of the data packet. All other replicas are being sent to the first encountered relay node (AUV). The first encountered relay node will store the data in its buffer until it meets another node in its communication range. While encountering another relay, it will send half of the replicated data packets to the next-hop relay node, and the process continues till they are left with only a single copy or if it has reached the destination. Once the destination is reached the nodes will go to the waiting phase and transmit the copies of the message to the corresponding destination. The process is described in Fig. 8.

Routing in PROPHET (Probabilistic Routing Protocol uses the History of Encounters and Transitivity) makes use of non-random and well-defined properties for data propagation. The scenario here is also the same as mentioned for the spray and wait protocol. In this work, a delivery predictability metric has been introduced. The predictability metric will be high if a node is in frequent contact with a location or with a node. The packet should be sent from the source node to the destination sink node. For this, the source copies the data packet to the first encountered relay node (AUV). And later, if this relay node gets in contact with another relay node, they compare their predictability metric among themselves. The message gets copied to the contacted node only if the predictability of the node is greater than the node carrying the message, otherwise, the same node will carry the message till it finds a node with a larger predictability metric (Lindgren et al., 2012).

Flooding is another technique used in a mobile network where the location of the nodes is not determined. This is simply a broadcast technique. If the source node wants to send a message to the destination it will simply broadcast it. But this creates frequent collisions and greater overheads, especially in an acoustic environment. Therefore, the authors in Goel et al. (2008) have introduced COFSNET - Controlled Flooding for Small Network of AUVs. This is a case of limited flooding which makes use of the packet sequence number to ensure that the same packet is not broadcasted more than once in any node in a network.

Probabilistic broadcast is another technique introduced in Koseoglu et al. (2016) for dense AUV networks where the nodes or AUVs are not aware of the neighbour's location. In this process, the nodes will retransmit the packet with respect to a probability in order to reduce the number of messages.

RAPID (Replication-Based DTN Routing Protocols Under Investigation) (Hossen and Rahim, 2015) is another replication-based protocol where the packets are replicated in a controlled manner and the aim of the RAPID is to optimize a specific routing metric such as average delay, missed deadlines, or maximum delay. RAPID relies on a utility function and derives a per-packet utility function from the routing metric.

3. Location Based Routing Protocol

In location-based routing/geographic routing, routes are established with the aid of location information (Hao et al., 2018; Coutinho et al., 2013). It requires the position of its neighbours and the destination node to be available in order to form a route from the source to destination. Location information is made available with the localization techniques, on the other hand depends upon the fine-grained time synchronization protocol. Some of the location-based protocols are described below.

A heterogeneous scenario is described in Pei et al. (2019). There are static sink nodes at the surface and three AUVs are used for data collection. The work speaks about three modes of communication. Upstream communication where the packet is sent by AUV to sink nodes. Downstream where the packets are sent by sink nodes to AUV.

And finally between AUVs where the packets are sent by one AUV to other AUVs.

In this work it is assumed that the AUVs, though mutative (likely to undergo changes), know their location in real-time via acoustic modems, advanced localization techniques and depth gauge. Here, the geographic routing protocol called Mobile Sink Hop by Hop Vector-Based Forwarding (MS-HH-VBF) has been used (Pei et al., 2019). It is an advanced version of Hop by Hop Vector-Based forwarding (HH-VBF) (Nicolaou et al., 2007) and Vector-Based Forwarding protocol (VBF) (Xie et al., 2006). These are two routing protocols that support small to medium range mobility.

In VBF, a routing vector is defined to specify the route from source to the destination. The packet forwarder nodes in the network form a "routing pipe". The nodes in the pipe are eligible for packet forwarding while the nodes which are not closed to the routing vectors are ineligible for packet forwarding. Whereas, HH-VBF is adapted to use the routing vector for the individual forwarder node rather than a single network-wide source-to-sink routing vector. On the other hand, MS-HH-VBF makes use of multiple sink nodes in order to cope with AUV's mobility.

In MS-HH-VBF, the geographic location of multiple sink nodes are stored in each data packet. This helps the receiver nodes to collect information about the accurate location of the sink nodes. Then, each forwarder calculates the distance between the multiple sinks and choose the nearest one as a destination to build the pipeline. The process is similar to that of HH-VBF. But, while dealing with the downstream communication and inter-AUV routing, the protocol collapses as the destination is no longer static and it uses flooding based routing for both the streams.

Sector-based Routing with Destination Location Prediction (SBR-DLP) is a location-based routing protocol designed for UWMSN (Chirdchoo et al., 2009). It assumes that a node knows its own location and predicts the location of the destination node. This helps to achieve a higher Packet Delivery Ratio (PDR). This protocol supports the destination node's mobility making it suitable for a fully mobile network.

Mobil and Co-Mobil are two routing protocols proposed to reduce the localization error in an underwater network (Javaid et al., 2017b). In a network consisting of static underwater sensor nodes, localization is done based on the reference nodes at the surface. The nodes which are closer to the surface nodes consider the anchor nodes at the surface as the reference nodes while those which are away from the anchors can only take the ordinary nodes as the reference. This adds to the localization error. Thus in this work, three AUVs are employed to serve as the reference. The AUVs get the position coordinates at the surface via GPS and satellites and dive back to the depth to provide the reference. AUVs are also capable of covering a larger volume.

Co-Mobil is a cooperative Mobil introduced for improving the network throughput by using the Maximal Ratio Combining (MRC) diversity technique which combines the signal from the source as well as relay nodes.

A trajectory aware communication in gliders with WHOI Micro-modem is proposed in Chen et al. (2010a). Usually, the trajectories of the gliders are sawtooth in nature and used for location prediction. In geographic routing, it is assumed that the locations are known prior. But these protocols are not considering the saw-toothed trajectories while making routing decisions. This increases the localization errors while estimating the glider location.

In order to overcome the disparities, this work put forward a statistical approach to predict the glider position. Instead of considering the glider's position as a single point, a confidence region is introduced. The unicast routing protocol developed here ensures the routing of packets to all the gliders in a specific geographic region. The cross-layer optimization combined with the routing helps to minimize energy consumption.

Position-Aware Mobility Pattern (PAMP) and cooperative PAMP (Co-PAMP) is proposed in Javaid et al. (2017a). PAMP is developed as an optimization scheme that deals with the avoidance of voids and helps in the minimization of uncertainty in a glider's position estimation. While Co-PAMP deals with the cooperative routing scheme that helps to lower the packet drop ratio by using relay cooperation.

Another interesting geographic algorithm named as the greedy perimeter stateless routing is adopted for routing in the network layer (Karp and Kung, 2000) for a swarm of vehicles are introduced in Tabacchiera et al. (2011). This work mainly targets designing suitable sensor nodes for the mobile underwater system by considering a Cross-Layer solution, which is applicable for the lower layers of the node. The essence of the work lies in maintaining the power consumption to a minimum level, without adding any complexity to the architectural design. Assuming that the inter-vehicular distance is not more than 25 m, with relatively lesser traffic. A simple MAC protocol such as ALOHA/CSMA is considered and further, a power control strategy was implemented, where the transmitted power is set to a minimum level. This claims to preserve the power of the whole network by reducing useless redundant hops towards nodes far from the final destination as the location of the nodes are already known.

P-AUV is another location based protocol. This is basically a cross-layer between the routing and MAC protocol in Bereketli et al. (2019). It depends on location estimation at each node. This protocol does not propagate the state, location and neighbourhood information in the network. Each node estimates its current position and mission path based on its knowledge from its initial deployment and inbuilt navigation systems in each AUV. This protocol supports the ad-hoc communication of AUVs in both vertical and horizontal directions. The algorithm is not in need of time-synchronization among AUVs. Carrier sensing and loop-free routing prevent collisions and re-transmissions to avoid additional energy losses and medium access delays. The AUVs decide to relay packets according to their positions. A random backoff duration has to be chosen before a node starts its packet transmission, which depends on its distance to the source. Nodes farther from the source are prioritized to decrease packet delivery delay and the number of collisions. Directed routes are accomplished along the source-to-sink path. If the node senses the channel is busy at the end of the backoff duration, it selects another random backoff duration and attempts to transmit again.

4. AUV Aided Data Collection

This category aims at data collection using AUVs from the static sensor nodes which are deployed for long term and large scale networks.

A routing protocol is known as AURP (AUV aided Underwater Routing Protocol) which makes use of the controlled mobility of multiple AUVs is described in Yoon et al. (2012). The data transmissions are minimized using multiple AUVs as relay nodes. The scenario described is a heterogeneous network where the AUVs need to collect the data from the gateway nodes and relay that to the sink nodes at the surface. With the controlled mobility of AUV, authors aimed at achieving short-range communication having a high data rate. This helps in the transmission of large amounts of data.

AEDG (AUV-aided Efficient Data Gathering Routing Protocol) (Ilyas et al., 2015) is another protocol that makes use of AUV for reliable data collection. It claims that using mobile AUV for collecting the data from the gateway nodes will prolong the network lifetime. This could minimize the energy consumption by employing SPT (Shortest Path Tree) algorithm while associating the sensor nodes with the gateway nodes.

Here, the gateway nodes are rotated in order to balance the energy consumption. Additionally, to prevent data loss, this protocol allows dynamic data collection time to AUV depending upon the count of sensor nodes to the gateway. A Mixed Integer Linear Programming (MILP) model was also formulated here to increase the throughput and minimize energy consumption.

AA-RP (AUV-Aided Routing Method Integrated Path Planning) (Wang et al., 2017), is a protocol that aims at reducing network energy. This integrates the dynamic path planning algorithms into the routing

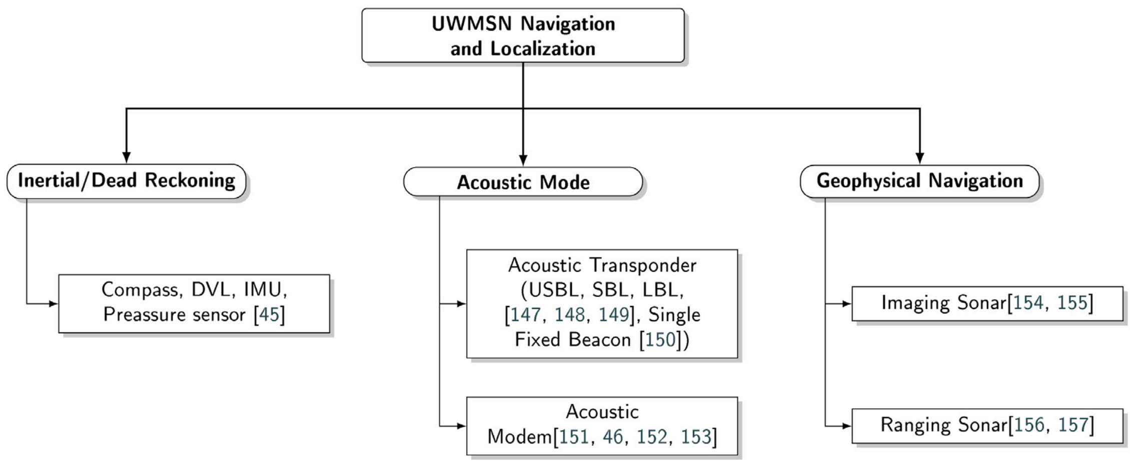


Fig. 9. Classification of Navigation and Localization Techniques of Underwater Sensor Networks (Paull et al., 2013; Rigby et al., 2006; Arrichiello et al., 2012; Han et al., 2012; LaPointe, 2006; Maczka et al., 2007; Bahr et al., 2009; Paull et al., 2014; Vaganay et al., 2004; Maurelli et al., 2009; Ribas, 2005; Li et al., 2013; Fallon et al., 2011).

protocols. This method relies on two phases:-AAR (AUV-Aided network Routing) and RAPP (Routing Aided Path Planning) AA-RP utilizes the cooperation of multi-tasks to reduce energy consumption for the network and avoids hot spot and zone problems with dynamic GN (Gateway Node) schemes.

Mobicast routing protocol is proposed in Chen et al. (2010b). This protocol mentions the mobility and topology-hole problem. The protocol assumes that a mobile sink or AUV, having a predefined trajectory is continuously collecting data from nodes within a series of 3D zones of reference (3D ZOR). Energy Efficient Mobicast protocol is proposed in Huang et al. (2003), in order to save energy the nodes in the particular zones are only awakened before the AUV's entry into the particular zone.

Mobile Energy Efficient Square routing protocol (MEES) is proposed in Walayat et al. (2017), as a method to prolong the network lifetime by balancing the energy consumption of nodes in the network. There are two mobile nodes that are deployed at maximum distance from each other. These nodes are supposed to move linearly in the clockwise direction, in their predefined trajectories. The energy efficiency is achieved by sending the data in static nodes to the AUV directly, instead of opting for multi-hop transmission which often results in hot-spot problems and latency.

A Cross-Layer Mobile Data gathering (CLMD) is another protocol introduced in Alfouzan et al. (2020). Here, an AUV is used to visit the deployed clusters where the data has been collected. The network performance was boosted by using a distributed cross-layer solution to enhance the network performance in terms of packet delivery and energy saving.

EPBR (Estimate-Position Based Routing) described in Signori et al. (2018) speaks about the routing protocol that decides the next hop, based on the estimated position of the AUV. The estimates are done by the static nodes. These nodes collect the position and direction of movement of the AUVs from information available in the packets exchanged among the nodes. The nodes know their position and routes to the neighbouring nodes. The information is disseminated in the network using the flooding technique or directly stored in each node even before deployment.

4. Prominence of localization and time synchronization in mobile underwater network

Localization and Time Synchronization plays a big role in cooperative missions with multiple underwater vehicles. It is of prime importance to know the location of each other and to have a common notion of time for effective communication among the vehicles. This section gives an insight into localization and time synchronization.

4.1. Navigation and localization

Based on a predefined strategy, underwater vehicles navigate autonomously underwater. Localization and mapping are two of its components. The role of localization is to provide the AUVs with their position and orientation information in order to find their traversal path. Mapping provides AUVs with environmental information for path planning, obstacle avoidance and goal-seeking. The localization becomes harder when it comes to underwater due to the unavailability of Global Positioning System (GPS), harsh channel conditions and complex marine environment (Sahoo et al., 2019).

In an underwater environment, navigation and localization is usually carried out in three modes such as inertial, acoustic and geophysical navigation as shown in Fig. 9. Inertial navigation relies on various sensor data to estimate the vehicle's relative velocity and position. Different sensors are used in the Inertial Measurement Unit (IMU) such as an accelerometer, gyroscope and magnetometer to provide data related to the acceleration, rotational speed and magnetic field intensity. The Doppler Velocity Log (DVL) sonar provides relative velocity positioning data from GPS while the depth data is taken from the pressure sensors. Acoustic navigation makes use of acoustic transponders and modems. This technique depends upon the Time of Flight (ToF) of signals from acoustic beacons or modems to perform navigation. Based on the placement of acoustic transponders, three methods are available. They are (1) Ultra-Short Baseline (USBL), (2) Short Baseline (SBL), and (3) Long Baseline (LBL) techniques (Paull et al., 2013; Rigby et al., 2006; Arrichiello et al., 2012; Han et al., 2012).

In USBL, transducers mounted on the transceivers are very closely packed, extending the baseline to approximately 10 cm. The relative range calculations are done by measuring the TOF and the bearing by the phase difference of the signals reaching the transceivers. In SBL, beacons are positioned at two opposite sides of the ship hull and the baseline comes to be the size of the ship (Rigby et al., 2006). In the LBL system, beacons are placed at the sea bed and while using the GPS Intelligent Buoys (GIBs), the beacons are placed at the surface. They are usually used for a wide area and uses the method of triangulation of acoustic signals for localization.

Acoustic modems embedded in the AUVs are another method used as the communication enablers of navigational data. They are used to transmit the information along with the signal used for range estimation using TOF. Thus relieving the use of fixed transponders. However, the unavailability of GPS signals makes the navigation of AUVs challenging. This makes the vehicles rely upon the information gained through the sensors mounted on the AUVs, such as compass, pressure sensors, DVL or an Inertial Navigation System (INS) (Bahr et al., 2009; Paull et al., 2014).

Despite the quality of the sensors used, it is found that the error occurred due to the position estimation subjected to the dead-reckoning is increasing. For vehicles travelling at a range of a few hundred metres on the seafloor, having their DVL locked to the bottom is showing a navigation error up to 0.5–2 per cent of the distance travelled. The errors can be further reduced to even 0.1 per cent by using huge and costly INS systems. But, in the case of vehicles relying on a compass and a speed estimate, errors can be as high as 20 per cent.

Although, the AUV can make position updates through GPS upon surfacing, this cannot be desirable in many instances. The operational area gets shrunk to a few kilometres while using static beacons from the LBL array in deep water conditions.

The idea of a single fixed beacon is introduced in LaPointe (2006). This reduces the cost and time of installing multiple beacons and georeferencing them, as it uses only a single fixed beacon. The concept adopted here is to simulate the baseline by continuously transmitting ranges from the single beacon until the reception of the next update. This technique is also named as VLBL (Virtual Long Base Line).

This sheds further scope for the idea of cooperative navigation. Cooperative Navigation is the term first coined by Rekleitis et al. (2001) in the terrestrial multi robotic application. Cooperative navigation gained its prominence in an application involving large numbers of AUVs with relatively less capability, thus allowing each individual member of the group to obtain information from other members in the group. This technique outperforms the dead reckoning technique by reducing the rate of position uncertainty growth in the case of vehicles working as a team. Greater the number of members in the team, the lesser uncertainty subjected to the law of diminishing returns (Vaganay et al., 2004).

Cooperative localization algorithm is proposed in Allotta et al. (2014). It explains a tetrahedral geometric method using a minimum of three AUVs. All the AUVs consist of an INS and one of them has a DVL, that can aid Cooperative Localization (CL) using acoustic communication. In CL, vehicles are aware of the position estimates of each other. The range estimates of the sender and receiver vehicles are measured by determining the TOF of the transmission and the Sound of Speed (SoS) in the water using Eq. (20). The SoS in water is taken as 1500 m/s.

$$Relative\ Range = ToF \times SoS \tag{20}$$

The requirement for optimal cooperative localization is described in Bahr et al. (2009). This work introduced the use of Communication and Navigation Aid-AUVs (C/NAs), which helps to maintain the accuracy in the position estimate using DVL and INS sensors. The setup is otherwise known as ‘underwater GPS in a local area’.

The AUVs with different capabilities can form a heterogeneous fleet. They cooperatively navigate with greater navigation precision without frequent surfacing for GPS measurements. The fleet is mainly used for rapid search applications in large areas. The network consists of C/NA AUVs, Search-Classify-Map (SCM) AUVs, and Reacquire-Identify (RI) AUVs.

The Micro-modems by WHOI aided in the development of integrated communication and navigation, especially for smaller AUVs. One of the navigational capabilities of the Micro-modem is that it is compatible with REMUS’ broadband digital transponders, bluefin AUVs etc.

Cooperative Autonomy for Distributed Reconnaissance and Exploration (CADRE) system is explained in Vaganay et al. (2004). It talks about the Moving Long Base-Line (MLBL) navigation concept. The vehicles with C/NA assume to provide a reference for lesser capable vehicles equipped with compass based navigation. The configuration of the vehicles is such that the C/NAs are placed on the sides and at the rear side of the cadre vehicles. This resembles the two-beacon moving long baseline array. And this is used by the lesser capable SCM and RI vehicles. Time synchronization is done to the vehicles with respect to GPS time and maintained even at the time of submerging with the aid of highly stable oscillators. This makes a greater advantage for the SCM and RI vehicles to determine their range using C/NA by listening to the pings, but they need to know the ping time. This is solved by pre-scheduling ping times and/or informing the cadre vehicles, of the ping sequence through an initialization broadcast.

Whereas, a work carried out in Fallon et al. (2010a) shows that one or more surface vehicles are acting as C/NA supporting an AUV. The surface vehicle acts as a communication and control moderator for the team of vehicles and simultaneously provides its position and range estimates to the AUV so that it could use that information to better navigate. In the scenario explained in Vaganay et al. (2004), two surface vehicles are used to estimate the full state vector of the AUV at once. Another configuration is explained in Fallon et al. (2010b), where a single C/NA supports an Iver2 AUV, and can itself be extended in a straightforward fashion to support any number of AUVs within the range of transmission.

A decentralized CL algorithm is presented in Paull et al. (2014) . The algorithm is designed for full trajectory or maximum a posteriori estimation of AUVs. The algorithm has the advantage that the size of the broadcast packet get increased only linearly, with the number of AUVs in the fleet and stops growing further in the case of packet loss. The efficiency of the mission is achieved by the reduction in surfacing time for the GPS fixes and through the smoothing approach, the payload data gets accurately localized.

A cooperative bathymetry-based localization for low-cost AUVs is proposed in Tan et al. (2016) The AUVs are fitted only with a single-beam altimeter, a depth sensor and an acoustic modem. The localization of individual AUV’s are achieved through fully decentralized particle filtering, with the local filter’s measurement model driven by the AUV’s altimeter measurements and ranging information obtained through inter-vehicle communication. The method claims to prolong the AUV mission time and thereby enhance the concept of long-term underwater autonomy.

A homogeneous fleet of AUVs for cooperative navigation (all the vehicles are of similar nature) is proposed in Maczka et al. (2007). The Virginia Tech 475 AUVs are used here. They are small, streamlined AUVs that displace approximately 8.2 kg each and are equipped with WHOI Micro-Modems. The vehicles are time synchronized. The data transmission aims at calculating the relative range between the vehicles. Along with other information, the relative range of vehicles used for cooperative navigation is transmitted. Due to the conditions like low bandwidth and latency of the underwater medium, it is difficult to implement a standard Kalman filter for cooperative navigation. The bandwidth is insufficient to share the data needed to accurately propagate the estimation error covariance matrix. As a result, sharing only a scalar function of the main diagonal elements of the covariance matrix would suffice.

Geophysical Navigation uses external environmental features as landmarks for localization. Sonars are used in the acoustic category for geophysical navigation. Simultaneous Localization and Mapping (SLAM) is majorly used for this navigation. This is again classified into imaging sonars and ranging sonars.

Imaging sonars usually comes with (a) side-scan sonar, (b) forward-looking sonars and (c) mechanically scanned imaging sonars. The acoustic returns from the seabed are recorded continuously as cross-track slices. The image of the seabed is formed when the series of cross-track slices are combined together along with the direction of travel (Maurelli et al., 2009; Ribas, 2005).

In the case of ranging sonar, multi-beam sonar, echo sounder and profilers are used. In multi-beam sonar, instead of single transducers, there are multiple such beams from the array of transducers mounted on the ship hull. Here, the beams reach the seafloor at different angles and are received by the AUVs at slightly different instances. This gets further converted into the bathymetric maps (Fallon et al., 2011).

4.2. Time synchronization

It is of greater importance in underwater applications involving shared goals to have a common notion of time. That is, the nodes should be synchronized to coordinate and collaborate with each other to achieve their task. The desired accuracy of time synchronization depends upon the requirement of the application and the specific purpose of synchronization. Certain applications of sensor networks need the right chronology of the events to be detected (for example, target tracking application), while some applications need the absolute time of the events to be made available (for example, disaster prevention system) (Zhou et al., 2018; Valls et al., 2015). Many important protocols in the sensor network (for example, TDMA based MAC protocol) cannot work without achieving time synchronization (Claesson et al., 2001). For such cases, time synchronization protocol in the sensor network is indispensable. Time synchronization also marks its imprints in various other networking protocols such as localization and distributed data aggregation.

The time synchronization algorithms developed for terrestrial networks cannot be used in underwater environments due to high propagation delay. Synchronization overhead is the main concern in an underwater environment, due to the low data rate resulting from a relatively narrow bandwidth. An accurate synchronization without the need for frequent re-synchronization is desirable in underwater environments.

Mobility is another major challenge to address. The underwater environment is always dynamic which incurs mobility in sensor nodes even if it is not self-propelled. There are two main factors that contribute to the pronounced effect of mobility on the performance of underwater time synchronization. The first one is the variation in the propagation delay. It depends on the relative speed of the nodes. For instance, in the case of devices like drifters and gliders which are not self-propelled and move with a maximum speed of 1 m/s but apparently their relative speed can be as high as 2 m/s. Whereas self-propelled vehicles can speed up to 4 m/s.

The second impact due to mobility is the delay incurred to the node before transmission, that is in order to avoid packet collisions, the nodes will randomly back off. It is highly probable for the nodes moving with a relative speed of 2 m/s to drift to a larger distance at the order of even tens of metres. This will translate to the timing uncertainty in the order of milliseconds (Lu et al., 2010).

There are various time synchronization algorithms that support mobility. TSHL is the first algorithm that takes into account the high propagation delay in underwater networks. However, it is designed for static networks (Syed et al., 2006). A cluster-based synchronization algorithm termed as MU-sync for UWMSN is proposed in Chirdchoo et al. (2008). This algorithm claims to avoid frequent re-synchronization by estimating and compensating the clock skew and offset using a two-phase operation. The skew and offset acquisition phase, and the synchronization phase. During the initial phase, the clock skew and offset is estimated by applying linear regression twice over a set of 'n' reference beacons. The linear regression is performed twice here to retrieve the estimated skew.

The first linear regression enables the cluster head to offset the effect of long and varying propagation delay; the second regression, in turn, obtains the estimated skew and offset. With the help of MAC-level time stamping, the non-deterministic errors that are commonly encountered by those synchronization algorithms are reduced. MU-Sync is not considered to be energy efficient when compared with TSHL due to a large number of two-way message exchanges. MU-Sync takes the assumption that the one-way propagation delay is estimated from the average round trip time. However, for the mobile entities which are at constant motion, there are greater chances for the one-way propagation delay to get easily biased. In addition to that, the nodes have to back off for a random time before starting the transmission to the cluster head. Also, the performance of the MU-Sync gets greatly affected when there are a large number of nodes resulting in longer time durations.

Mobi-Sync is another algorithm designed to support mobility (Liu et al., 2012). It employs the spatial correlation of sensor node mobility and helps in improving the accuracy of the fast-changing propagation delay. The network categorizes nodes into three categories. They are the (1) surface buoys having GPS to get the reference time, (2) supernodes capable of maintaining the synchronization and (3) ordinary nodes to implement the time synchronization. The ordinary nodes broadcast request messages to the supernodes and supernodes respond to them by sending a message containing its absolute velocity.

This algorithm works in three phases and is designed to acquire ordinary nodes' clock drift by estimating their clock skew and offset. Phase one is the delay estimation with mobility correlation where propagation delay is estimated by taking advantage of the spatial correlation of node mobility. Phase two is linear regression where the ordinary node performs linear regression over a set of timestamps as well as propagation delays. While phase three is calibration done to patch up the assumptions in phase one. As initial parameters like distance and initial skew are unknown during phase one, the ordinary node selects rough values for each of them. To correct errors derived from those rough initial parameters, the ordinary node updates the initial parameters and re-performs computing. The protocol demands a correlation model to estimate the node's velocity with respect to the supernode. However, it is very difficult to obtain accurate correlation models between the nodes while estimating the time-varying delay.

D-Sync (Lu et al., 2010) is proposed as an algorithm robust to mobility by incorporating the physical layer information. It makes use of an estimate of Doppler shift. Doppler shift is the main impairment due to mobility in underwater communication. Therefore, it should be estimated and compensated. This work utilizes the information contained in the Doppler shift. As the Doppler shift gives information about the node's motion, it is utilized to obtain the timing uncertainty caused by the node's mobility. However, it does not consider the clock skew during the process of estimating the Doppler scaling factor. This reduces the accuracy of the Doppler shift estimation and affects the accuracy of time synchronization. As a result, the accuracy of time synchronization gets declined with an increase in the initial skew.

DA-Sync (Liu et al., 2013) is a time synchronization protocol that proposes a framework to estimate the Doppler shift caused by mobility more precisely through accounting for the impact of the clock skew. Kalman filter is employed to enhance the time synchronization by refining the velocity estimation. The clock skew and offset are calibrated by two runs of linear regression.

While DE-Sync proposed in Zhou et al. (2018) takes clock skew into account for estimating the Doppler scale factor and substitutes in linear regression to get the estimation of clock skew and offset.

APE-Sync (Adaptive Power-Efficient time Synchronization) is proposed in Zhou et al. (2019). It combines the DE-Sync and the Kalman filter tracking the clock skew to achieve time synchronization. The advantage of this protocol is that it helps in the reduction of energy consumption and offers more accurate synchronization.

Joint solution for localization and time synchronization is proposed in Liu et al. (2015) and Yi et al. (2015). The stratification effect of the underwater medium is considered in Liu et al. (2015). The bias in the range estimates, caused by assuming sound waves travel in straight lines in water environments is thus compensated. It is seen that by combining time synchronization and localization, the accuracy of both is improved jointly. An advanced tracking algorithm IMM (Interactive Multiple Model) is adopted here to improve the accuracy of localization in the mobile case. By combining both services, the number of required exchanged messages is significantly reduced, which saves on energy consumption.

Authors in Yi et al. (2015) investigates the time synchronization and tracking of submersibles, that only have the capability to receive

Table 3
Various test beds and their specifications.

Test bed & the developing organizations	Short description	Modems and specification	Network components
PLUSNet by WHOI	Heterogeneous network developed for Anti-Submarine Warfare (ASW)	WHOI Micro-modem, 80 bps with FSK, 300–5000 bps with phase coherent modulation	Gateway buoys, Fixed bottom nodes , Seaglider AUVs as Mobile Gateway, Bluefin AUVs, and XRay Glider
Sea Web by US Navy	Wide-area network for long-term synoptic observation for under sea wireless network development	Telesonar modems, 800 bp/s with MFSK modulation	Racom buoy, gateway nodes, repeater nodes , AUV glider mobile node-SLOCUM gliders
RACUN project by European Defense Agency	Based on the requirement of different naval organizations	Develogic acoustic modem	The ATLAS SeaCat AUV, AUV 62 of SAAB US, L3 ELAC Nautic gateway buoy, NILUS sensor node (DIFAR version)
FP7 UAN Project by European Union	A network that spans aerial, surface and underwater nodes	Acoustic modem manufactured by Kongsberg Maritime (KM), 200 bps to 1600 bps	eFolaga AUV, Subsurface Telemetry Unit (STU), underwater Fixed Nodes (FNOs)
3D Aquatic test bed by Naval Air Warfare Center Weapons Division, Weapons and Energetics, China	Developing a test bed for cooperative mission using miniature vehicles in aquatic test bed	–	SUB-SONIC XP -recreational class models of AUVs

acoustic signals. The locations of submersibles are tracked by long-baseline systems having few reference beacons in reference locations. These systems make use of the Time Difference of Arrival (TDoA) for localization. It is assumed that TDoA makes the beacon transmissions occur nearly concurrent in time. However, this can be used in small LBL deployments and does not support as the size of the system scales up. This work points out the scenarios where signals from multiple beacons are significantly lagged in time and further identified that the motion of the submersible between signal arrivals is the key factor that deteriorates the performance of TDoA when transmissions are not concurrent. The problem is tackled here by tracking the submersible while performing time synchronization. The proposed technique, called Time of Arrival based Tracked Synchronization (ToA-TS) essentially extends GPS like localization for scenarios where beacon transmissions are not concurrent and submersibles are not capable of two-way communication.

The following section describes some of the prominent works carried out in UWMSN. Software developments for UWMSN as well as the real-time deployments/testbeds are also covered.

5. Prominent works on mobile underwater networks

Several works have been carried out across the globe, in academia and research centres to develop and implement the simulation and real-time testbeds for tasks involving multiple underwater vehicles. The platforms used for the simulation and experimentation usually consists of software-based components, underwater modems, static as well as mobile sensor nodes and user interfaces (Chitre et al., 2008; Luo et al., 2017). This section gives some insight into the field of software as well as testbed developments.

5.1. Software developments for mobile underwater network

Development in the field of software is most important to mimic the underwater environment. Simulation tools, protocol stack, OS etc. are the most important components coming under the software. There are various types of software tools available such as commercial, customized-developed by researchers and free open-source software.

This is used to simulate the underwater acoustic channel behaviour by using various models (for example, the ray-tracing models). The real-time environmental data such as bathymetry profile, sound speed profile, bottom sediment etc. from the ocean databases can be made used in simulations. The various simulators available are the platforms to conduct various experiments with simplicity, repeatability and flexibility in terms of network size, mode, traffic pattern and topology. This helps in comparing and evaluating different network designs, algorithms and protocols. Prominent simulation environments are listed below with their desired functionalities.

(1) Aqua Sim:- Aqua Sim (Nayyar and Balas, 2019; Xie et al., 2009), is an NS-2 based discrete-event network simulator developed by the Underwater Sensor Networks Lab at the University of Connecticut, for underwater networks. The open-source software supports three-dimensional static and mobile networks. Aqua-Sim effectively simulates the attenuation of underwater acoustic channels and the collision behaviours in long delay acoustic networks. It implements all the layers from the physical to the application layer. Two languages are used in NS-2 are C++ and Otcl. Users can use Otcl scripts to easily tune the parameters of protocols and algorithms are implemented in C++. In Aqua-Sim network entities are implemented as classes in C++.

(2) WOSS (World Ocean Simulation System):- WOSS (Guerra et al., 2009; Casari et al., 2014) is developed by the NATO Undersea Research center. It supports heterogeneity in the network. This is a multi-threaded C++ framework where the physical layer modelling, as well as cross-layer specification of networking protocols, are supported. It permits the integration of any existing underwater channel simulator that expects environmental data as input and provides channel realization as output. A Bellhop ray-tracing tool is incorporated for a more realistic reproduction of underwater propagation. And NS2-MIRACLE is used for flexible programming of the protocol stack. NS2-MIRACLE is the extended version of NS2 that adds many new libraries to enhance the information exchange mechanism for cross-layer design and optimization and several modules can co-exist simultaneously in the same layer with little interaction. In WOSS the user only has to specify the location in the world and the time where the simulation should take place. It is integrated with free world databases for environmental parameters which are used in the simulation of the UASN protocols.

(3) UNET:- UNET is developed by the NUS, Singapore (Chitre et al., 2014, 2012; Zhu et al., 2014). It has started at the Acoustic Research Laboratory (ARL) of the National University of Singapore in 2004. It supports the heterogeneity of the network. This provides a platform for unifying the simulation and implementation framework, thus giving a chance to translate simulation studies to sea trials with little added effort. This is composed of UnetStack (an agent-based network stack) and an Underwater Network Simulator used for the development and testing of underwater network technology. The simulator was designed with two key goals (i) easy to learn and use, and (ii) permit agent implementations to be shared between the deployment environment and simulation environment.

(4) UUV Simulator (Unmanned Underwater Vehicle (UUV) Simulator):- UUV Simulator (Song et al., 2020), is developed by the Corporate Sector for Research and Advanced Engineering and Fraunhofer-Institute of Optronics, System Technologies. It is built as a modified version of the open-source robotics simulator Gazebo to work

in underwater scenarios. Plugins are implemented in the simulator to model underwater hydrostatic and hydrodynamic effects, thrusters, sensors, and external disturbances. It can reuse the existing robotic platform in an underwater environment.

(5) DESERT (DEsign, Simulate, Emulate and Realize Testbeds for Underwater network protocols) (Masiero et al., 2012; Nayyar and Balas, 2019) is the platform developed under the NAUTILUS Project funded by the Italian Institute of Technology. This is developed in 2012 as an open-source simulation, emulation, and experimental tool, based on NS2 and NS2-MIRACLE. The architecture of DESERT is designed in such a way that the physical layer provides the interface between the simulator and real hardware modems like Micro-Modems, Ecologic modems. The mobility modules implemented here is having four different 2D or 3D mobility models to simulate underwater robot movement. The NS2-MIRACLE architecture also gives scope for interfacing hardware devices and provides valid outcomes while evaluating the performance of user-designed applications and protocols and also improves its simulation accuracy by connecting itself to specific underwater channel model tools such as WOSS. Moreover, it can integrate real hardware modems into the simulation process for creating a more realistic environment while developing high-performance protocols and applications.

5.2. Test-bed and real-time deployments of cooperative mobile networks

The underwater research being a costly affair, the experimental research with so many mobile vessels are quite exemplary. Various testbeds and real-time deployment are listed as in Table 3.

PLUSNet by WHOI:- PULSENet (Persistent Littoral Undersea Surveillance Network) comprises of multiple sensors and vehicles to serve as Anti-Submarine Warfare (ASW) communication network. The network is capable of providing autonomous detection and tracking of quiet submarines in support of the Navy Sea Power 21 concept. This needs an adaptive network that could support mobility as well as environmental changes.

The physical layer is based on the WHOI Micro-modem. It uses two modulation methods and supports multiple data rates. The frequency-hopping FSK with rate-limited to 80 bps, and phase-coherent with variable length block and spreading codes spanning approximately 300–5000 bps at four different rates. Its MAC protocol takes two forms such as centrally arbitrated and random access. Three modes are used in the random access. They are (1) centrally managed round-robin polling from one of two gateway buoys under control from shore, (2) random access without acknowledgement for status datagrams, and (3) random access with acknowledgement for event messages. The network layer helps to store and forward routing of messages that will travel more than one hop (Grund et al., 2006).

Sea Web Program:- The sea web was developed by Space and Naval Warfare Systems Command (SPAWAR), Office of Naval Research (ONR), Navy laboratories under the US Navy undersea wireless networking program. It is meant for long term observation in a very large area that spans thousands of kilometres. The physical layer in the network leans towards the numerical physics-based channel models and channel simulations. A portable tele sonar testbed is used for controlled sea measurements with high-fidelity signal transmission, reception, and data acquisition. The reliability in the data link layer is ensured by the implementation of negative acknowledgements, range-dependent timers, retries and automatic repeat requests. In the Network layer, Neighbour-Sense Multiple Access (NSMA), a network layer functionality that passively observes the Sea web traffic to discover the communications status of Neighbour nodes is implemented (Rice and Green, 2008).

The RACUN-Project:- The RACUN project was undertaken by the Research and Development initiative set up by the European Research Institutes and Industry sponsored by European Defence Agency (EDA). As the project was initiated by the navies of vivid interests instead of developing various applications, it rather considered generic applications capable of defining multi-purpose networks. The operation area described here includes mobile as well as static sensors which cooperatively works on the basis of event-driven logic. The trials were done in the North Sea and Mediterranean (Kalwa, 2011).

UAN Project:- This is a European Union (EU) funded project. This project stands on the concept of ensuring the protection of both offshore as well as the coastline. It relies on an infrastructure having multiple sensor networks. These networks are connected to a command and control (C2) centre, which helps in integrating the data collected from all the aerial, terrestrial, surface and underwater sensors.

AUVs are considered as the mobile nodes in the network. The role of the AUVs is to adapt to the geometry of the network taking into account the variations occurring in the acoustic channel. The network was working for five continuous working days with five nodes of which three of them are mobile. The FP7 project spanned from 2008 to 2011 and had its final demonstration in the Trondheim fjord in Norway (Caiti et al., 2012b).

Cooperative Search with Autonomous Vehicles in a 3D Aquatic Testbed:- The work was carried out by the Naval Air Warfare Center Weapons Division, Weapons and Energetics, China. The project aims at building a very small aquatic testbed that supports miniature vehicles that could scale to a range of centimetres. Radio signals are used for communication, but it is rather challenging to design and control miniature vehicles (Keeter et al., 2012).

The following section describes the recent advancement in the field of UWMSN. The concepts of Underwater Internet of Things (UIoT), Cognitive Ocean of Things (COT) and Network Management System (NMS) are discussed briefly.

6. Recent advancements in the field of UWMSN

UIoT (Domingo, 2012; Qiu et al., 2019; Zhang et al., 2020) is a promising technology emerging for developing the smart oceans. This is an extended version of IoT in terrestrial networks, designed for ocean environments. The UIoT is considered as a smart network with intelligent computing and self-learning capabilities.

This complex heterogeneous system with flexible layered architecture consists of mainly three layers such as application layer, network layer, and perception layer. An Advanced UIoT architecture was proposed in Qiu et al. (2019) with five layers such as application, fusion, networking, communication, and sensing layers working independently with scalability. UIoT is advancing with the current technologies such as cloud computing, fog computing and artificial intelligence to make a big leap in ocean monitoring systems. For instance, cloud computing paves the way to model an on-demand model for network access to a shared pool of computing resources with minimal management efforts. Fog computing is a time-sensitive virtualized platform capable of providing computing, storage, and networking services to end devices and traditional cloud servers. UIoT solves several challenges like object targeting, event detection, data transmission, network security and quality of service using machine learning algorithms in artificial intelligence.

COT is explained in Li et al. (2019) and Lu et al. (2019). It evolves as a general-purpose intelligence cognition technology. It has four layers: perception sensors (edge) layer; local processing (fog) layer; cloud computing layer; and application layer. Cognitive artificial intelligence for sensing or computing the data is used in each layer. The challenges of such a network are addressed in terms of self-management, energy efficiency, communication coverage, fog and cloud computing.

However, due to the continuous growth of devices in networks, it seems to be a great deal to manage the infrastructure, device maintenance, device security, power conservation etc. This mandates an Underwater Network Management System (U-NMS) (Raj et al., 2020; Urunov et al., 2018) to monitor and control the devices in a network. This allows access to the network management and device management information of UIoT networks. The U-NMS architecture in UIoT is the combination of different networks, such as terrestrial IoT networks and UIoT networks. U-NMS is installed in the management station which is set up in the terrestrial IoT networks. The terrestrial IoT networks consist of the components such as a management station, manager, database, etc., and devices such as Base Station (BS), Surface Gateway (S-GW), etc. that uses RF and acoustic technologies. Whereas the UIoT network consists of intelligent underwater devices such as Underwater-Sensor Node (UW-SNode), Unmanned Underwater Vehicle (UUV), Underwater-Cluster Head (UW-CH), etc. These are also installed with agent software that is used for sensing, collecting and transferring data.

7. Conclusion and the lessons learned

This paper presents a detailed review of ocean phenomena monitoring using the Underwater Mobile Sensor Network (UWMSN). This review will help to get an insight into how mobility can bring greater advancement to the traditional underwater networks. Further, this will showcase the transition of a network with controlled mobility (i.e, with few mobile entities) to a network comprising a fleet of AUVs. The need for using these multi-AUV networks along with the challenges of designing these networks are also discussed.

The focus of this work is to bring a birds-eye view on the ways, the networks of AUVs are built based on a specific application requirement. Then a concise view of the design and development of various techniques and protocols used in different layers of the UWMSN protocol stack is presented. One of our major findings is that, still there exists a greater scope in defining a scalable network for larger spatial and temporal extents. However, there are rarely fewer works that consider a distributed mission with these fleets to form a real application scenario with their own, spatial and temporal extents. Moreover, most of these networking protocols are explained for a small swarm of AUVs. Even though, there is a sharp rise in the miniaturization of AUVs, to cut down the cost, time, efforts in deployment and network efficiency the networking of this is still nascent. There are many opportunities for further research in these networks to explore short distance, high data rate communication. There is a huge development in the field of miniaturization of modems too, like WHOI micro modems are available for these AUVs.

Considering the underwater channel, it is less forgiving in nature and creates uncertainty in reliable communication. There are lot many contexts that still exist, apart from its innate nature. For example, the case of very shallow water, the navigation through icebergs remains a cumbersome game. This gives further scope for making the distinction among these channels. They behave very differently while considering the vertical and horizontal links, in shallow and deep water. So there is a need for standardization of the channel models to get a better fit in the required scenario. There is also a scope for applying digital signal processing to acoustic communication for better efficiency (Song et al., 2019). The design of feedback-based acoustic systems is another aspect. Giving the feedback from the receiver to the transmitter side to adaptively chose in terms of power, modulation, positioning and directive transmission can give a newer aspect to acoustic communication systems.

Focusing on the case of the protocols stack of UWMSN the networking could be at much ease if the nature of the underwater environment is considered, for example, the network protocol is designed to tolerate the end-to-end delay, the role of oceanic effects, low bandwidth high energy consumption and so on. The spatiotemporal variability of the underwater networks is made use of in some of the works described in this work by giving chances for concurrent transmissions. Enabling cross-layer communication among the layers would help to improve the network performance such that the MAC protocol was designed such that to bring down the power consumption.

One of the major constraints while dealing with the UWMSN is the mobility of nodes/AUVs. Most of the papers dealing with these networks are not addressing the optimization of paths followed by these vehicles. Proper path planning along with communication among AUVs would bring a theoretic approach. For an effective swarm to evolve there should be a balance between the sensing communication and positioning of the vehicles. Sometimes referred to as swarm intelligence. This paper tried to highlight interesting algorithms related to the positioning of AUVs like cooperative localization algorithms for AUV swarms.

The simulators for mimicking these fleets would also require some attention. Though mobility models are supported by those simulators, it is of great importance to check the reach of these simulators in the oceanic environment. In most of these simulators, the vehicles are considered as point objects without considering their kinematic constraints and oceanic forces. And efforts are appreciated to bring the simulated environment much more realistic in terms of channel models, mobility patterns etc.

In this era of the smart ocean, the ocean observation system has turned to be smatter with new technologies like UIoT, Software-defined Underwater Networks, Information and communication technologies etc. These technologies has to bring several smart devices of heterogeneous capabilities from different manufacturers or sources under an umbrella. But the interoperability of these devices or operational consistency are not often supported. Therefore NATO Center for Maritime Research and Engineering has developed a standard known as JANUs (Potter et al., 2014). And more recently Sonardyne along with the UK Ministry of Defence's Defence Science and Technology Laboratory (Dstl) is trying to develop a high-integrity secure waveform for acoustic communications (Ball, 2021). This new standard will aid the navies to interoperate the vehicles with security. So there is a need for developing more such standards for secure and reliable underwater communication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ahmed, M., Salleh, M., Channa, M.I., 2017. Routing protocols based on node mobility for underwater wireless sensor network (UWSN): A survey. J. Netw. Comput. Appl. 78, 242–252.

Ainslie, M.A., McColm, J.G., 1998. A simplified formula for viscous and chemical absorption in sea water. J. Acoust. Soc. Am. 103 (3), 1671–1672.

Akyildiz, I.F., Pompili, D., Melodia, T., 2005. Underwater acoustic sensor networks: Research challenges. Ad Hoc Netw. 3 (3), 257–279.

Alfouzan, F.A., Ghoreyshi, S.M., Shahrabi, A., Ghahroudi, M.S., 2020. A novel cross-layer mobile data-gathering protocol for underwater sensor networks. In: 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring). IEEE, pp. 1–6.

Allen, B., Austin, T., Forrester, N., Goldsborough, R., Kukulya, A., Packard, G., Purcell, M., Stokey, R., 2006. Autonomous docking demonstrations with enhanced REMUS technology. In: OCEANS 2006. IEEE, pp. 1–6.

Allotta, B., Costanzi, R., Meli, E., Pugi, L., Ridolfi, A., Vettori, G., 2014. Cooperative localization of a team of AUVs by a tetrahedral configuration. Robot. Auton. Syst. 62 (8), 1228–1237.

Andrea Sacco, 2010. GSOC2010UANFramework. URL: https://www.nsnam.org/wiki/GSOC2010UANFramework.

Arrichiello, F., Heidarsson, H.K., Sukhatme, G.S., 2012. Opportunistic localization of underwater robots using drifters and boats. In: 2012 IEEE International Conference on Robotics and Automation. IEEE, pp. 5307–5314.

Ayaz, M., Baig, I., Abdullah, A., Faye, I., 2011. A survey on routing techniques in underwater wireless sensor networks. J. Netw. Comput. Appl. 34 (6), 1908–1927.

Babin, M., Roesler, C.S., Cullen, J.J., 2008. Real-Time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling. Unesco.

Bahr, A., Leonard, J.J., Fallon, M.F., 2009. Cooperative localization for autonomous underwater vehicles. Int. J. Robot. Res. 28 (6), 714–728.

Ball, M., 2021. New open standard for secure underwater communications, URL: https://www.unmannedsystemstechnology.com/2021/06/new-open-standard-for-secure-underwater-communications/.
Bayat, B., Crasta, N., Crespi, A., Pascoal, A.M., Ijspeert, A., 2017. Environmental monitoring using autonomous vehicles: A survey of recent searching techniques. Curr. Opin. Biotechnol. 45, 76–84.
Benton, C., Kenney, J., Nitzel, R., Blidberg, R., Chappell, S., Mupparapu, S., 2004. Autonomous undersea systems network (AUSNET)-protocols to support ad-hoc AUV communications. In: 2004 IEEE/OES Autonomous Underwater Vehicles (IEEE Cat. No. 04CH37578). IEEE, pp. 83–87.
Bereketli, A., Tumcakir, M., Yazgi, I., Yeni, B., Koseoglu, M., Duman, T.M., 2017. Connectivity analysis of an AUV network with OFDM based communications. In: 2017 IEEE Underwater Technology (UT). IEEE, pp. 1–5.
Bereketli, A., Tümçakır, M., Yeni, B., 2019. P-AUV: Position aware routing and medium access for ad-hoc auv networks. J. Netw. Comput. Appl. 125, 146–154.
Bouabdallah, F., 2019. Time evolution of underwater sensor networks coverage and connectivity using physically based mobility model. Wirel. Commun. Mob. Comput. 2019.
Brekhovskikh, L., Lysanov, I., 1991. Fundamentals of Ocean Acoustics. In: Springer Series in Electrophysics, Springer-Verlag.
Burian, E., Yoerger, D., Bradley, A., Singh, H., 1996. Gradient search with autonomous underwater vehicles using scalar measurements. In: Proceedings of Symposium on Autonomous Underwater Vehicle Technology. IEEE, pp. 86–98.
Burrowes, G.E., 2014. Underwater swarm sensor networks: Applications, deployment, and medium access communication protocols.
Burrowes, G.E., Brown, J., Khan, J.Y., 2013. Adaptive space time-time division multiple access (AST-TDMA) protocol for an underwater swarm of AUV's. In: 2013 MTS/IEEE OCEANS-Bergen. IEEE, pp. 1–10.
Burrowes, G.E., Khan, J.Y., 2009. Adaptive token polling MAC protocol for wireless underwater networks. In: 2009 4th International Symposium on Wireless Pervasive Computing. IEEE, pp. 1–5.
Cabral, H.M.P., 2014. Acoustic modem for underwater communications.
Caiti, A., Calabrò, V., Munafò, A., 2012a. AUV team cooperation: Emerging behaviours and networking modalities. IFAC Proc. Vol. 45 (27), 342–347.
Caiti, A., Husoy, T., Jesus, S., Karasalo, I., Massimelli, R., Munafò, A., Reinen, T., Silva, A., 2012b. Underwater acoustic networks: The Fp7 UAN project. IFAC Proc. Vol. 45 (27), 220–225.
Camilli, R., Reddy, C.M., Yoerger, D.R., Van Mooy, B.A., Jakuba, M.V., Kinsey, J.C., McIntyre, C.P., Sylva, S.P., Maloney, J.V., 2010. Tracking hydrocarbon plume transport and biodegradation at deepwater horizon. Science 330 (6001), 201–204.
Cannell, C.J., Gadre, A.S., Stilwell, D.J., 2006. Boundary tracking and rapid mapping of thermal plume using an autonomous vehicle. In: OCEANS 2006. IEEE, pp. 1–6.
Carlson, E.A., Beaujean, P.-P., An, E., 2006. Location-aware routing protocol for underwater acoustic networks. In: OCEANS 2006. IEEE, pp. 1–6.
Caruso, A., Paparella, F., Vieira, L.F.M., Erol, M., Gerla, M., 2008. The meandering current mobility model and its impact on underwater mobile sensor networks. In: IEEE INFOCOM 2008-the 27th Conference on Computer Communications. IEEE, pp. 221–225.
Casari, P., Tapparello, C., Guerra, F., Favaro, F., Calabrese, I., Toso, G., Azad, S., Masiero, R., Zorzi, M., 2014. Open source suites for underwater networking: WOSS and DESERT underwater. IEEE Netw. 28 (5), 38–46.
Centelles, D., Soriano, A., Marti, J.V., Sanz, P.J., 2020. Underwater multirobot cooperative intervention MAC protocol. IEEE Access 8, 60867–60876.
Chen, B., Hickey, P.C., Pompili, D., 2010a. Trajectory-aware communication solution for underwater gliders using WHOI micro-modems. In: 2010 7th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON). IEEE, pp. 1–9.
Chen, Y.-S., Lin, Y.-W., Lee, S.-L., 2010b. A mobicast routing protocol in vehicular ad-hoc networks. Mob. Netw. Appl. 15 (1), 20–35.
Chen, C.-T., Millero, F.J., 1977. Speed of sound in seawater at high pressures. J. Acoust. Soc. Am. 62 (5), 1129–1135.
Chen, B., Pandey, P., Pompili, D., 2012. An adaptive sampling solution using autonomous underwater vehicles. IFAC Proc. Vol. 45 (27), 352–356.
Cheng, C.-F., Li, L.-H., 2017. Data gathering problem with the data importance consideration in underwater wireless sensor networks. J. Netw. Comput. Appl. 78, 300–312.
Cherkaoui, E.H., Toni, L., Rossi, L., Fontaine, J.-G., Agoulmine, N., 2011. On the effects of node mobility on energy efficiency and delay sensitive applications in underwater sensor network. In: OCEANS 2011 IEEE-Spain. IEEE, pp. 1–6.
Chirdchoo, N., Soh, W.-S., Chua, K.C., 2008. MU-sync: A time synchronization protocol for underwater mobile networks. In: Proceedings of the Third ACM International Workshop on Underwater Networks. pp. 35–42.
Chirdchoo, N., Soh, W.-S., Chua, K.C., 2009. Sector-based routing with destination location prediction for underwater mobile networks. In: 2009 International Conference on Advanced Information Networking and Applications Workshops. IEEE, pp. 1148–1153.
Chitre, M., Bhatnagar, R., Soh, W.-S., 2014. UnetStack: An agent-based software stack and simulator for underwater networks. In: 2014 Oceans-St. John's. IEEE, pp. 1–10.
Chitre, M., Shahabudeen, S., Stojanovic, M., 2008. Underwater acoustic communications and networking: Recent advances and future challenges. Mar. Technol. Soc. J. 42 (1), 103–116.
Chitre, M., Topor, I., Koay, T.-B., 2012. The UNET-2 Modem—An extensible tool for underwater networking research. In: 2012 Oceans-Yeosu. IEEE, pp. 1–7.
Cho, A.-R., Yun, C., Lim, Y.-K., Choi, Y., 2018. Asymmetric propagation delay-aware TDMA MAC protocol for mobile underwater acoustic sensor networks. Appl. Sci. 8 (6), 962.
Claesson, V., Lonn, H., Suri, N., 2001. Efficient TDMA synchronization for distributed embedded systems. In: Proceedings 20th IEEE Symposium on Reliable Distributed Systems. IEEE, pp. 198–201.
Coates, R.F., 1990. Underwater Acoustic Systems. Macmillan International Higher Education.
Coppens, A.B., 1981. Simple equations for the speed of sound in neptunian waters. J. Acoust. Soc. Am. 69 (3), 862–863.
Coutinho, R.W., Boukerche, A., 2018. Exploiting mobility to improve underwater sensor networks. In: Proceedings of the 16th ACM International Symposium on Mobility Management and Wireless Access. pp. 89–94.
Coutinho, R.W., Vieira, L.F., Loureiro, A.A., 2013. Movement assisted-topology control and geographic routing protocol for underwater sensor networks. In: Proceedings of the 16th ACM International Conference on Modeling, Analysis & Simulation of Wireless and Mobile Systems. pp. 189–196.
Dabrowski, T., Lyons, K., Nolan, G., Berry, A., Cusack, C., Silke, J., 2016. Harmful Algal bloom forecast system for SW Ireland. Part I: Description and validation of an operational forecasting model. Harmful Algae 53, 64–76.
Daladier, J.M., Labrador, M.A., 2009. A data link layer in support of swarming of autonomous underwater vehicles. In: OCEANS 2009-EUROPE. IEEE, pp. 1–10.
Danielis, P., Parzyjegla, H., Ali, M.A.M., Torres, F.S., 2021. Simulation model for energy consumption and acoustic underwater communication of autonomous underwater vehicles. WMU J. Marit. Aff. 1–19.
Das, J., Rajany, K., Frolovy, S., Pyy, F., Ryany, J., Caronz, D.A., Sukhatme, G.S., 2010. Towards marine bloom trajectory prediction for AUV mission planning. In: 2010 IEEE International Conference on Robotics and Automation. IEEE, pp. 4784–4790.
Del Grosso, V.A., 1974. New equation for the speed of sound in natural waters (with comparisons to other equations). J. Acoust. Soc. Am. 56 (4), 1084–1091.
Dhongdi, S.C., Nahar, P., Sethunathan, R., Gudino, L.J., Anupama, K., 2017. Cross-layer protocol stack development for three-dimensional underwater acoustic sensor network. J. Netw. Comput. Appl. 92, 3–19.
Diamant, R., Lampe, L., 2010. A hybrid spatial reuse MAC protocol for ad-hoc underwater acoustic communication networks. In: 2010 IEEE International Conference on Communications Workshops. IEEE, pp. 1–5.
Domingo, M.C., 2008. Overview of channel models for underwater wireless communication networks. Phys. Commun. 1 (3), 163–182.
Domingo, M.C., 2012. An overview of the internet of underwater things. J. Netw. Comput. Appl. 35 (6), 1879–1890.
Domingo, M.C., Prior, R., 2008. Energy analysis of routing protocols for underwater wireless sensor networks. Comput. Commun. 31 (6), 1227–1238.
Egbo, H., Hallin, N., Ray, P., O'Rourke, M., Frenzel, J., Edwards, D., 2009. Token-based medium access control solution for underwater acoustic broadcast. In: OCEANS 2009. IEEE, pp. 1–9.
Fallon, M.F., Kaess, M., Johannsson, H., Leonard, J.J., 2011. Efficient AUV navigation fusing acoustic ranging and side-scan sonar. In: 2011 IEEE International Conference on Robotics and Automation. IEEE, pp. 2398–2405.
Fallon, M.F., Papadopoulos, G., Leonard, J.J., 2010a. A measurement distribution framework for cooperative navigation using multiple AUVs. In: 2010 IEEE International Conference on Robotics and Automation. IEEE, pp. 4256–4263.
Fallon, M.F., Papadopoulos, G., Leonard, J.J., 2010b. Cooperative AUV navigation using a single surface craft. In: Field and Service Robotics. Springer, pp. 331–340.
Farrell, J.A., Pang, S., Li, W., 2005. Chemical plume tracing via an autonomous underwater vehicle. IEEE J. Ocean. Eng. 30 (2), 428–442.
Felemban, E., Shaikh, F.K., Qureshi, U.M., Sheikh, A.A., Qaisar, S.B., 2015. Underwater sensor network applications: A comprehensive survey. Int. J. Distrib. Sens. Netw. 11 (11), 896832.
Fisher, F., Simmons, V., 1977. Sound absorption in sea water. J. Acoust. Soc. Am. 62 (3), 558–564.
Franchi, M., Pecorella, T., Ridolfi, A., Fantacci, R., Allotta, B., 2017. Kinematic constraints and ns-3 mobility models: The AUV issue. In: Proceedings of the Workshop on Ns-3. pp. 103–109.
Francois, R., Garrison, G., 1982a. Sound absorption based on ocean measurements: Part I: Pure water and magnesium sulfate contributions. J. Acoust. Soc. Am. 72 (3), 896–907.
Francois, R., Garrison, G., 1982b. Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption. J. Acoust. Soc. Am. 72 (6), 1879–1890.
Freitag, L., Grund, M., Singh, S., Johnson, M., 2000. Acoustic communication in very shallow water: Results from the 1999 AUV fest. In: OCEANS 2000 MTS/IEEE Conference and Exhibition. Conference Proceedings (Cat. No. 00CH37158), Vol. 3. IEEE, pp. 2155–2160.
Freitag, L., Grund, M., Von Alt, C., Stokey, R., Austin, T., 2005. A shallow water acoustic network for mine countermeasures operations with autonomous underwater vehicles. Underw. Def. Technol. (UDT) 1–6.

Fullmer, C.L., Garcia-Luna-Aceves, J., 1995. Floor acquisition multiple access (FAMA) for packet-radio networks. In: Proceedings of the Conference on Applications, Technologies, Architectures, and Protocols for Computer Communication. pp. 262–273.

Ghoreyshi, S.M., Shahrabi, A., Boutaleb, T., 2017. Void-handling techniques for routing protocols in underwater sensor networks: Survey and challenges. IEEE Commun. Surv. Tutor. 19 (2), 800–827.

Gilabert, J., López Castejon, F., Guerrero, A., Molina, J., Vasilijevic, A., Calado, P., Hayes, D., Stilinovic, N., Nad, D., Mandic, F., et al., 2015. Underwater robotics ready for oil spill, an EU project. Instrum. Viewp. (18), 54.

Goel, A., Kannan, A.G., Katz, I., Bartoš, R., 2008. Improving efficiency of a flooding-based routing protocol for underwater networks. In: Proceedings of the Third ACM International Workshop on Underwater Networks. pp. 91–94.

Green, D., 2016. Old and new concepts in undersea networks. In: OCEANS 2016-Shanghai. IEEE, pp. 1–6.

Grund, M., Freitag, L., Preisig, J., Ball, K., 2006. The PLUSNet underwater communications system: Acoustic telemetry for undersea surveillance. In: OCEANS 2006. IEEE, pp. 1–5.

Guerra, F., Casari, P., Berni, A., Potter, J., Zorzi, M., 2010. Performance evaluation of random and handshake-based channel access in collaborative mobile underwater networks. In: OCEANS 2010 MTS/IEEE SEATTLE. IEEE, pp. 1–7.

Guerra, F., Casari, P., Zorzi, M., 2009. World ocean simulation system (WOSS): A simulation tool for underwater networks with realistic propagation modeling. In: Proceedings of the Fourth ACM International Workshop on UnderWater Networks. pp. 1–8.

Guo, Z., Wang, B., Cui, J.-H., 2010. Prediction assisted single-copy routing in underwater delay tolerant networks. In: 2010 IEEE Global Telecommunications Conference GLOBECOM 2010. IEEE, pp. 1–6.

Hajenko, T., Benson, C., 2010. The high frequency underwater acoustic channel. In: OCEANS'10 IEEE SYDNEY. IEEE, pp. 1–3.

Han, G., Jiang, J., Shu, L., Xu, Y., Wang, F., 2012. Localization algorithms of underwater wireless sensor networks: A survey. Sensors 12 (2), 2026–2061.

Hao, K., Shen, H., Liu, Y., Wang, B., Du, X., 2018. Integrating localization and energy-awareness: A novel geographic routing protocol for underwater wireless sensor networks. Mob. Netw. Appl. 23 (5), 1427–1435.

Harrison, T., 2021. Buoyancy Controlled Float Swarms for Distributed Sensing in Coastal Waterways (Ph.D. thesis). University of Washington.

Havelock, D., Kuwano, S., Vorländer, M., 2008. Handbook of Signal Processing in Acoustics. Springer Science & Business Media.

Heidemann, J., Stojanovic, M., Zorzi, M., 2012. Underwater sensor networks: Applications, advances and challenges. Phil. Trans. R. Soc. A 370 (1958), 158–175.

Ho, I.W.-H., Chau, S.C.-K., Magsino, E.R., Jia, K., 2019. Efficient 3D road map data exchange for intelligent vehicles in vehicular fog networks. IEEE Trans. Veh. Technol. 69 (3), 3151–3165.

Hollinger, G.A., Mitra, U., Sukhatme, G.S., 2011. Autonomous data collection from underwater sensor networks using acoustic communication. In: 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, pp. 3564–3570.

Hossen, M.S., Rahim, M.S., 2015. Performance evaluation of replication-based DTN routing protocols in intermittently connected mobile networks. In: 2015 International Conference on Electrical & Electronic Engineering (ICEEE). IEEE, pp. 101–104.

Huang, Q., Lu, C., Roman, G.-C., 2003. Mobicast: Just-in-time multicast for sensor networks under spatiotemporal constraints. In: Information Processing in Sensor Networks. Springer, pp. 442–457.

Ilyas, N., Alghamdi, T.A., Farooq, M.N., Mehboob, B., Sadiq, A.H., Qasim, U., Khan, Z.A., Javaid, N., 2015. AEDG: AUV-aided efficient data gathering routing protocol for underwater wireless sensor networks. Procedia Comput. Sci. 52, 568–575.

INET Core Team, 2021. INET mobility models. URL: https://inet.omnetpp.org/docs/showcases/mobility/basic/doc/.

Jakuba, M., Yoerger, D., Bradley, A., German, C., Langmuir, C., Shank, T., 2005. Multi-scale, multimodal AUV surveys for hydrothermal vent localization. In: Proceedings of the Fourteenth International Symposium on Unmanned Untethered Submersible Technology (UUST05).

Javaid, N., Ejaz, M., Abdul, W., Alamri, A., Almogren, A., Niaz, I.A., Guizani, N., 2017a. Cooperative position aware mobility pattern of AUVs for avoiding void zones in underwater WSNs. Sensors 17 (3), 580.

Javaid, N., Maqsood, H., Wadood, A., Niaz, I.A., Almogren, A., Alamri, A., Ilahi, M., 2017b. A localization based cooperative routing protocol for underwater wireless sensor networks. Mob. Inf. Syst. 2017.

Jiang, Z., 2008. Underwater acoustic networks–Issues and solutions. Int. J. Intell. Control Syst. 13 (3), 152–161.

Johnson, D., Hu, Y.-c., Maltz, D., et al., 2007. The Dynamic Source Routing Protocol (DSR) for Mobile Ad-hoc Networks for IPv4. Technical Report, RFC 4728.

Kalkan, K., 2011. A Key Distribution Scheme for Mobile Underwater Wireless Sensor Networks (Master's thesis). Mühendislik ve Fen Bilimleri Enstitüsü.

Kalwa, J., 2011. The RACUN-project: Robust acoustic communications in underwater networks—An overview. In: OCEANS 2011 IEEE-Spain. IEEE, pp. 1–6.

Karn, P., et al., 1990. MACA-a new channel access method for packet radio. In: ARRL/CRRL Amateur Radio 9th Computer Networking Conference, Vol. 140. London, Canada, pp. 134–140.

Karp, B., Kung, H.-T., 2000. GPSR: Greedy perimeter stateless routing for wireless networks. In: Proceedings of the 6th Annual International Conference on Mobile Computing and Networking. pp. 243–254.

Keeter, M., Moore, D., Muller, R., Nieters, E., Flenner, J., Martonosi, S.E., Bertozzi, A.L., Percus, A.G., Levy, R., 2012. Cooperative search with autonomous vehicles in a 3-D aquatic testbed. In: 2012 American Control Conference (ACC). IEEE, pp. 3154–3160.

Kemna, S., Rogers, J.G., Nieto-Granda, C., Young, S., Sukhatme, G.S., 2017. Multi-robot coordination through dynamic voronoi partitioning for informative adaptive sampling in communication-constrained environments. In: 2017 IEEE International Conference on Robotics and Automation (ICRA). IEEE, pp. 2124–2130.

Khalifeh, A., Rajendiran, K., Darabkh, K.A., Khasawneh, A.M., AlMomani, O., Zinonos, Z., 2019. On the potential of fuzzy logic for solving the challenges of cooperative multi-robotic wireless sensor networks. Electronics 8 (12), 1513.

Kinsler, L., Frey, A., Coppens, A., Sanders, J., 1982. Transmission phenomena. In: Fundamentals of Acoustics. John Wiley and Sons, pp. 124–140.

Kleinrock, L., Tobagi, F., 1975. Packet switching in radio channels: Part I-Carrier sense multiple-access modes and their throughput-delay characteristics. IEEE Trans. Commun. 23 (12), 1400–1416.

Koseoglu, M., Bereketli, A., Yazgi, I., Yeni, B., 2016. Probabilistic broadcast for dense AUV networks. In: OCEANS 2016 MTS/IEEE Monterey. IEEE, pp. 1–5.

Kumar, S.V., Jayaparvathy, R., Priyanka, B., 2020. Efficient path planning of AUVs for container ship oil spill detection in coastal areas. Ocean Eng. 217, 107932.

Lanbo, L., Shengli, Z., Jun-Hong, C., 2008. Prospects and problems of wireless communication for underwater sensor networks. Wirel. Commun. Mob. Comput. 8 (8), 977–994.

LaPointe, C.E.G., 2006. Virtual Long Baseline (VLBL) Autonomous Underwater Vehicle Navigation using a Single Transponder (Ph.D. thesis). Massachusetts Institute of Technology.

Li, W., Farrell, J.A., Pang, S., Arrieta, R.M., 2006. Moth-inspired chemical plume tracing on an autonomous underwater vehicle. IEEE Trans. Robot. 22 (2), 292–307.

Li, J., Lee, M., Park, S., Kim, J., Kim, J., Suh, J., 2013. Development of P-SURO II hybrid AUV and its experimental study. In: 2013 MTS/IEEE OCEANS-Bergen. IEEE, pp. 1–6.

Li, Y., Takahashi, S., Serikawa, S., 2019. Cognitive ocean of things: A comprehensive review and future trends. Wirel. Netw. 1–10.

Lindgren, A., Doria, A., Davies, E., Grasic, S., 2012. Probabilistic Routing Protocol for Intermittently Connected Networks. RFC Series, Internet Research Task Force.

Liu, X., Du, X., Li, M., Wang, L., Li, C., 2021. A MAC protocol of concurrent scheduling based on spatial-temporal uncertainty for underwater sensor networks. J. Sensors 2021.

Liu, J., Wang, Z., Cui, J.-H., Zhou, S., Yang, B., 2015. A joint time synchronization and localization design for mobile underwater sensor networks. IEEE Trans. Mob. Comput. 15 (3), 530–543.

Liu, J., Wang, Z., Zuba, M., Peng, Z., Cui, J.-H., Zhou, S., 2013. DA-sync: A Doppler-assisted time-synchronization scheme for mobile underwater sensor networks. IEEE Trans. Mob. Comput. 13 (3), 582–595.

Liu, J., Zhou, Z., Peng, Z., Cui, J.-H., Zuba, M., Fiondella, L., 2012. Mobi-sync: Efficient time synchronization for mobile underwater sensor networks. IEEE Trans. Parallel Distrib. Syst. 24 (2), 406–416.

Lu, F., Mirza, D., Schurgers, C., 2010. D-sync: Doppler-based time synchronization for mobile underwater sensor networks. In: Proceedings of the Fifth ACM International Workshop on UnderWater Networks. pp. 1–8.

Lu, H., Wang, D., Li, Y., Li, J., Li, X., Kim, H., Serikawa, S., Humar, I., 2019. CONet: A cognitive ocean network. IEEE Wirel. Commun. 26 (3), 90–96.

Lu, X., Xin, Y., Lio, P., 2011. ADMAC: An adaptive directional MAC protocol for mobile ad-hoc networks. In: 2011 4th IEEE International Conference on Broadband Network and Multimedia Technology. IEEE, pp. 488–492.

Luo, H., Wu, K., Ruby, R., Hong, F., Guo, Z., Ni, L.M., 2017. Simulation and experimentation platforms for underwater acoustic sensor networks: Advancements and challenges. ACM Comput. Surv. 50 (2), 1–44.

Ma, S., 2014. A bio-inspired geomagnetic navigation model for AUV based on multi-objective evolutionary algorithm. In: 2014 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC). IEEE, pp. 495–498.

Ma, J., Lou, W., 2011. Interference-aware spatio-temporal link scheduling for long delay underwater sensor networks. In: 2011 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks. IEEE, pp. 431–439.

Mackenzie, K.V., 1981. Nine-term equation for sound speed in the oceans. J. Acoust. Soc. Am. 70 (3), 807–812.

Maczka, D.K., Gadre, A.S., Stilwell, D.J., 2007. Implementation of a cooperative navigation algorithm on a platoon of autonomous underwater vehicles. In: OCEANS 2007. IEEE, pp. 1–6.

Mandal, A.K., Misra, S., Ojha, T., Dash, M.K., Obaidat, M.S., 2017. Oceanic forces and their impact on the performance of mobile underwater acoustic sensor networks. Int. J. Commun. Syst. 30 (1), e2882.

Mao, J., Chen, S., Yu, J., Gu, Y., Yu, R., Xu, Y., 2016. LTM-MAC: A location-based TDMA MAC protocol for mobile underwater networks. In: OCEANS 2016 - Shanghai. pp. 1–5.

Masiero, R., Azad, S., Favaro, F., Petrani, M., Toso, G., Guerra, F., Casari, P., Zorzi, M., 2012. DESERT underwater: an NS-miracle-based framework to design, simulate, emulate and realize test-beds for underwater network protocols. In: 2012 Oceans-Yeosu. IEEE, pp. 1–10.
Maurelli, F., Petillot, Y., Mallios, A., Ridao, P., Krupinski, S., 2009. Sonar-based AUV localization using an improved particle filter approach. In: OCEANS 2009-EUROPE. IEEE, pp. 1–9.
Mazumder, S., Saha, K.K., 2006. Detection of oil seepages in oceans by remote sensing. In: Proceedings of the 6th International Conference & Exposition on Petroleum Geophysics.
Molins, M., Stojanovic, M., 2006. Slotted FAMA: a MAC protocol for underwater acoustic networks. In: OCEANS 2006-Asia Pacific. IEEE, pp. 1–7.
Monroy-Anieva, J.A., Rouviere, C., Campos-Mercado, E., Salgado-Jimenez, T., Garcia-Valdovinos, L.G., 2018. Modeling and control of a micro AUV: Objects follower approach. Sensors 18 (8), 2574.
Nayyar, A., Balas, V.E., 2019. Analysis of simulation tools for underwater sensor networks (UWSNs). In: International Conference on Innovative Computing and Communications. Springer, pp. 165–180.
Nicolaou, N., See, A., Xie, P., Cui, J.-H., Maggiorini, D., 2007. Improving the robustness of location-based routing for underwater sensor networks. In: Oceans 2007-Europe. IEEE, pp. 1–6.
Noh, Y., Lee, U., Han, S., Wang, P., Torres, D., Kim, J., Gerla, M., 2014. DOTS: A propagation delay-aware opportunistic MAC protocol for mobile underwater networks. IEEE Trans. Mob. Comput. 13 (4), 766–782.
Park, S.H., Mitchell, P.D., Grace, D., 2019. Reinforcement learning based MAC protocol (UW-ALOHA-Q) for underwater acoustic sensor networks. IEEE Access 7, 165531–165542.
Parrish, N., Roy, S., Fox, W.L., Arabshahi, P., 2007. Rate-range for an FH-FSK acoustic modem. In: Proceedings of the Second Workshop on Underwater Networks. pp. 93–96.
Paull, L., Saeedi, S., Seto, M., Li, H., 2013. AUV navigation and localization: A review. IEEE J. Ocean. Eng. 39 (1), 131–149.
Paull, L., Seto, M., Leonard, J.J., 2014. Decentralized cooperative trajectory estimation for autonomous underwater vehicles. In: 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, pp. 184–191.
Pei, P., Zhang, Y., Feng, W., Xu, Y., Xu, W., 2019. A heterogeneous network with multiple routing protocols for autonomous underwater vehicles. In: Proceedings of the International Conference on Underwater Networks & Systems. pp. 1–5.
Peleato, B., Stojanovic, M., 2007. Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks. IEEE Commun. Lett. 11 (12), 1025–1027.
Petillo, S., Balasuriya, A., Schmidt, H., 2010. Autonomous adaptive environmental assessment and feature tracking via autonomous underwater vehicles. In: OCEANS'10 IEEE SYDNEY. IEEE, pp. 1–9.
Petillo, S.M., Schmidt, H., 2012. Autonomous and adaptive underwater plume detection and tracking with AUVs: Concepts, methods, and available technology. IFAC Proc. Vol. 45 (27), 232–237.
Petillo, S., Schmidt, H., Balasuriya, A., 2011. Constructing a distributed AUV network for underwater plume-tracking operations. Int. J. Distrib. Sens. Netw. 8 (1), 191235.
Petrioli, C., Petroccia, R., Stojanovic, M., 2008. A comparative performance evaluation of MAC protocols for underwater sensor networks. In: OCEANS 2008. IEEE, pp. 1–10.
Pontbriand, C., Farr, N., Hansen, J., Kinsey, J.C., Pelletier, L.-P., Ware, J., Fourie, D., 2015. Wireless data harvesting using the AUV sentry and WHOI optical modem. In: OCEANS 2015-MTS/IEEE Washington. IEEE, pp. 1–6.
Potter, J., Alves, J., Green, D., Zappa, G., Nissen, I., McCoy, K., 2014. The JANUS underwater communications standard. In: 2014 Underwater Communications and Networking (UComms). IEEE, pp. 1–4.
Qiu, T., Zhao, Z., Zhang, T., Chen, C., Chen, C.P., 2019. Underwater internet of things in smart ocean: System architecture and open issues. IEEE Trans. Ind. Inf. 16 (7), 4297–4307.
Rahman, R.H., Benson, C., Jiang, F., Frater, M., 2013. LOARP: A low overhead routing protocol for underwater acoustic sensor networks. J. Netw. 8 (2), 317.
Rahman, R., Frater, M., 2015. Delay-tolerant networks (DTNs) for underwater communications. In: Advances in Delay-Tolerant Networks (DTNs). Elsevier, pp. 81–103.
Raj, K.M.D., Lee, J., Ko, E., Shin, S.-Y., Namgung, J.-I., Yum, S.-H., Park, S.-H., et al., 2020. Underwater network management system in internet of underwater things: Open challenges, benefits, and feasible solution. Electronics 9 (7), 1142.
Rekleitis, I., Dudek, G., Milios, E., 2001. Multi-robot collaboration for robust exploration. Ann. Math. Artif. Intell. 31 (1), 7–40.
Renner, C., Golkowski, A.J., 2016. Acoustic modem for micro AUVs: Design and practical evaluation. In: Proceedings of the 11th ACM International Conference on Underwater Networks & Systems. pp. 1–8.
Ribas, D., 2005. Towards Simultaneous Localization & Mapping for an AUV using an Imaging Sonar. Report on the Research Project, University de Girona, Girona, Spain.
Rice, J., Green, D., 2008. Underwater acoustic communications and networks for the US navy's seaweb program. In: 2008 Second International Conference on Sensor Technologies and Applications (Sensorcomm 2008). IEEE, pp. 715–722.
Rigby, P., Pizarro, O., Williams, S.B., 2006. Towards geo-referenced AUV navigation through fusion of USBL and DVL measurements. In: OCEANS 2006. IEEE, pp. 1–6.
Robbins, I.C., Kirkpatrick, G., Blackwell, S.M., Hillier, J., Knight, C.A., Moline, M.A., 2006. Improved monitoring of HABs using autonomous underwater vehicles (AUV). Harmful Algae 5 (6), 749–761.
Ryan, J., McManus, M., Kudela, R., Artigas, M.L., Bellingham, J., Chavez, F., Doucette, G., Foley, D., Godin, M., Harvey, J., et al., 2014. Boundary influences on HAB phytoplankton ecology in a stratification-enhanced upwelling shadow. Deep Sea Res. II 101, 63–79.
Sahoo, A., Dwivedy, S.K., Robi, P., 2019. Advancements in the field of autonomous underwater vehicle. Ocean Eng. 181, 145–160.
Salva-Garau, F., Stojanovic, M., 2003. Multi-cluster protocol for ad-hoc mobile underwater acoustic networks. In: Oceans 2003. Celebrating the Past... Teaming Toward the Future (IEEE Cat. No. 03CH37492), Vol. 1. IEEE, pp. 91–98.
Schill, F., Zimmer, U., 2007. Pruning local schedules for efficient swarm communication. In: 2007 Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies. IEEE, pp. 594–600.
Schill, F., Zimmer, U.R., et al., 2006. Distributed dynamical omnicast routing. Complex Syst. 16 (4), 299–316.
Schneider, T.E., 2013. Advances in Integrating Autonomy with Acoustic Communications for Intelligent Networks of Marine Robots (Ph.D. thesis). Massachusetts Institute of Technology.
Schulkin, M., Marsh, H., 1963. Absorption of sound in sea-water. Radio Electron. Eng. 25 (6), 493–500.
Shantaram, A., Beyenal, H., Veluchamy, R., Lewandowski, Z., 2005. The challenges of building scalable mobile underwater wireless sensor networks for aquatic applications. Environ. Sci. Technol. 39 (13), 5037–5042.
Shimura, T., Yukihiro, K., Deguchi, M., 2019. High-rate acoustic communication at the data rate of 69 kbps over the range of 3,600 m developed for vertical uplink communication. In: OCEANS 2019-Marseille. IEEE, pp. 1–6.
Signori, A., Campagnaro, F., Zorzi, M., 2018. Multi-hop range extension of a wireless remote control for underwater vehicles. In: 2018 OCEANS-MTS/IEEE Kobe Techno-Oceans (OTO). IEEE, pp. 1–7.
Singh, S., Webster, S.E., Freitag, L., Whitcomb, L.L., Ball, K., Bailey, J., Taylor, C., 2009. Acoustic communication performance of the WHOI micro-modem in sea trials of the nereus vehicle to 11,000 m depth. In: OCEANS 2009. IEEE, pp. 1–6.
Smith, S.M., Park, J.C., Neel, A., 1997. A peer-to-peer communication protocol for underwater acoustic communication. In: Oceans' 97. MTS/IEEE Conference Proceedings, Vol. 1. IEEE, pp. 268–272.
Song, Y., Nakath, D., She, M., Elibol, F., Köser, K., 2020. Deep sea robotic imaging simulator. arXiv preprint arXiv:2006.15398.
Song, A., Stojanovic, M., Chitre, M., 2019. Editorial underwater acoustic communications: Where we stand and what is next? IEEE J. Ocean. Eng. 44 (1).
Stojanovic, M., 2007. On the relationship between capacity and distance in an underwater acoustic communication channel. ACM SIGMOBILE Mob. Comput. Commun. Rev. 11 (4), 34–43.
Stojanovic, M., Beaujean, P.-P.J., 2016. Acoustic communication. In: Springer Handbook of Ocean Engineering. Springer, pp. 359–386.
Stojanovic, M., Freitag, L., Leonard, J., Newman, P., 2002. A network protocol for multiple AUV localization. In: OCEANS'02 MTS/IEEE, Vol. 1. IEEE, pp. 604–611.
Syed, A.A., Heidemann, J.S., et al., 2006. Time synchronization for high latency acoustic networks. In: Infocom, Vol. 6. pp. 1–12.
Tabacchiera, M., Marchetti, E., Betti, S., Persia, S., 2012. Configurations effects over swarm underwater acoustic network performance. In: SENSORCOM 2012, the Sixth International Conference on Sensor Technologies and Applications. IARIA, pp. 321–326.
Tabacchiera, M., Persia, S., Lodovisi, C., Betti, S., 2011. Performance analysis of underwater swarm sensor networks. In: 2011 International Conference on Broadband and Wireless Computing, Communication and Applications. IEEE, pp. 333–338.
Tan, Y.T., Chitre, M., Hover, F.S., 2016. Cooperative bathymetry-based localization using low-cost autonomous underwater vehicles. Auton. Robots 40 (7), 1187–1205.
Tholen, C., Nolle, L., 2017. Parameter search for a small swarm of auvs using particle swarm optimisation. In: International Conference on Innovative Techniques and Applications of Artificial Intelligence. Springer, pp. 384–396.
Tong, L., Qilu, Z., Linbo, Z., 2016. Modified AODV routing protocol in underwater acoustic networks. In: 2016 IEEE International Conference on Electronic Information and Communication Technology (ICEICT). IEEE, pp. 191–194.
Underwood, A., Murphy, C., 2017. Design of a micro-AUV for autonomy development and multi-vehicle systems. In: OCEANS 2017-Aberdeen. IEEE, pp. 1–6.
Urunov, K., Shin, S.-Y., Namgung, J.-I., Park, S.-H., 2018. Lightweight constrained management for the underwater—Network management system. Sensor Lett. 16 (9), 698–711.
Vaganay, J., Leonard, J.J., Curcio, J.A., Willcox, J.S., 2004. Experimental validation of the moving long base-line navigation concept. In: 2004 IEEE/OES Autonomous Underwater Vehicles (IEEE Cat. No. 04CH37578). IEEE, pp. 59–65.
Valls, O.P., Bouvet, P.-J., del Río, J., 2015. Hybrid time synchronization for underwater sensor networks. ACTA IMEKO 4 (3), 30–35.
Varma, M.K.N., Kalyani, M., Shin, S.-Y., Park, S.-H., 2019. Underwater Spray and Wait Routing Technique for Mobile Ad-hoc Networks. NISCAIR-CSIR, India.
Waite, A.D., 2002. Sonar for Practising Engineers. Wiley.

Walayat, A., Javaid, N., Akbar, M., Khan, Z.A., 2017. MEES: Mobile energy efficient square routing for underwater wireless sensor networks. In: 2017 IEEE 31st International Conference on Advanced Information Networking and Applications (AINA). pp. 292–297.
Wang, Z., Feng, X., Qin, H., Guo, H., Han, G., 2017. An AUV-aided routing protocol based on dynamic gateway nodes for underwater wireless sensor networks. J. Internet Technol. 18 (2), 333–343.
Xie, P., Cui, J.-H., Lao, L., 2006. VBF: Vector-based forwarding protocol for underwater sensor networks. In: International Conference on Research in Networking. Springer, pp. 1216–1221.
Xie, P., Zhou, Z., Peng, Z., Yan, H., Hu, T., Cui, J.-H., Shi, Z., Fei, Y., Zhou, S., 2009. Aqua-sim: An NS-2 based simulator for underwater sensor networks. In: OCEANS 2009. IEEE, pp. 1–7.
Yi, J., Mirza, D., Kastner, R., Schurgers, C., Roberts, P., Jaffe, J., 2015. ToA-TS: Time of arrival based joint time synchronization and tracking for mobile underwater systems. Ad Hoc Netw. 34, 211–223.
Yoon, S., Azad, A.K., Oh, H., Kim, S., 2012. AURP: An AUV-aided underwater routing protocol for underwater acoustic sensor networks. Sensors 12 (2), 1827–1845.
Yun, N.-Y., Kim, Y.-P., Muminov, S., Lee, J.-Y., Shin, S.-Y., Park, S.-H., 2011. Sync MAC protocol to control underwater vehicle based on underwater acoustic communication. In: 2011 IFIP 9th International Conference on Embedded and Ubiquitous Computing. IEEE, pp. 452–456.
Zenia, N.Z., Aseeri, M., Ahmed, M.R., Chowdhury, Z.I., Kaiser, M.S., 2016. Energy-efficiency and reliability in MAC and routing protocols for underwater wireless sensor network: A survey. J. Netw. Comput. Appl. 71, 72–85.
Zhang, Y., Chen, H., Xu, W., 2018. A load-adaptive CSMA/CA MAC protocol for mobile underwater acoustic sensor networks. In: 2018 10th International Conference on Wireless Communications and Signal Processing (WCSP). IEEE, pp. 1–7.
Zhang, J., Sha, J., Han, G., Liu, J., Qian, Y., 2020. A cooperative-control-based underwater target escorting mechanism with multiple autonomous underwater vehicles for underwater internet of things. IEEE Internet Things J. 8 (6), 4403–4416.
Zhou, F., Wang, Q., Han, G., Qiao, G., Sun, Z., Niaz, A., 2019. APE-sync: An adaptive power efficient time synchronization for mobile underwater sensor networks. IEEE Access 7, 52379–52389.
Zhou, F., Wang, Q., Nie, D., Qiao, G., 2018. DE-sync: A Doppler-enhanced time synchronization for mobile underwater sensor networks. Sensors 18 (6), 1710.
Zhu, Y., Pu, L., Wang, Z., Lu, X., Martin, R., Luo, Y., Peng, Z., Cui, J.-H., 2014. Underwater acoustic network protocol stacks: Simulator-based vs. OS-based. In: 2014 Oceans-St. John's. IEEE, pp. 1–7.

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