Review on Underwater sensor network challenges

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Abstract: Underwater acoustic networks deals with a network of sensors placed to monitor different parameters in the underwater environment. Acoustic medium is selected for data transmission from the underwater bed to the onshore station, and also between two nodes due to their suitability over radio or optical medium. Applications of underwater sensor network include monitoring of the ocean, navigation and surveillance applications. The dynamic underwater environment makes it difficult for the sensors to record and transmit data. Different architectures available for underwater sensor networks have been discussed. Challenges in routing information in underwater environment have been discussed. In this article, emphasis has been laid on some of the existing routing protocols and are being compared basing on different parameters**.**

***Index Terms* – Underwater sensor network. Challenges in acoustic communication**

I. INTRODUCTION

Underwater acoustic sensor networks have a wide range of applications for data collection from ocean, pollution monitoring, prevention of disasters, navigation and surveillance applications, undersea natural resource exploration and many more. Underwater Acoustic Sensor Network is made of nodes (Sensors) deployed to monitor the changes over a given area and convey the information through acoustic communication channel to the base station for future action. These nodes have capability to self organize and perform different tasks collaboratively i.e. they quickly adapt to the Ocean environment. The nodes must be able to communicate with each other and manage configuration data and settings and also coordinate information concerning their location and movement. Wireless acoustic transmission enables these applications. For terrestrial application radio frequency waves are used for communication whereas acoustic communication is employed for underwater applications.

a. Radio frequency waves are not employed for underwater networks

In underwater network environment, electromagnetic waves at high frequency cannot propagate to long distance as they get attenuated due to conducting environment of water and this attenuation increases with frequency. Sea water being conductive in nature absorbs electromagnetic waves and this limits the use of radio frequency waves. Therefore the next alternative is to use electromagnetic waves at low frequency (30-300 Hz).But for generation of electromagnetic waves at low frequency requires a large size antennae and also required transmission power would be high as the size of the antenna increases with decrease in frequency (for generating electromagnetic radiation of low frequency, the size of the antenna should be of one-tenth of wavelength of radiated signal). Therefore Radio frequency waves are not used for underwater communication. Berkeley Mica2 mote widely used for terrestrial sensor networks has a range of 120 cm at 433 MHz frequency in the underwater environment.

b. Optical transmission is not suitable for underwater communication

Optical waves may not suffer large attenuation but they are prone to scattering and absorption effects due to various constituents existing in water. Moreover, their transmission necessitates high precision as they use narrow laser beams for pointing. Generation of high precision narrow laser beam is quite a costly affair. Therefore, optical waves are used only for short-range communication in the underwater environment.

c. Differences between terrestrial sensor networks and underwater acoustic sensor networks

The primary difference between terrestrial and underwater sensor networks is the medium of communication. In the case of terrestrial networks, medium of communication is air and in underwater networks it is water.

Size of sensors used in terrestrial networks is quite smaller and inexpensive when compared to expensive underwater sensors. This is due to requirement of complex underwater transceivers and other equipment employed for protection of the device from ocean environment.

Power consumed is more in the case of underwater networks due to the presence of complex hardware equipment used for transmitting and receiving of the acoustic signal and also due to higher distances when compared to radio communication.

Memory required for terrestrial networks is less than that of underwater networks as the data has to be stored for self configuration in the case of underwater networks due to dynamic underwater environment. Real time position of nodes is required for designing routing protocols.

Dense Deployment: Terrestrial sensor networks employs large number of sensors (dense deployment) when compared to underwater sensor networks as the cost involved is less. Due to more number of sensors the readings obtained from them is quite co-related to each other. But the same is not the case with underwater medium as there are less number of sensors and also due to large distance between them.

Energy: The major challenge with underwater acoustic networks is the limited energy supply. In terrestrial networks the batteries used for the modem can be removed and replaced easily where as in acoustic networks it involves wastage of ship time and the retrieval of the modem battery from the ocean bottom is quite expensive and time-consuming. Therefore, energy efficient transmission protocols are considered in underwater applications. Network protocols should conserve energy by decreasing the number of retransmissions. Careful selection of routing protocols are required to move data from source node to sink node with less hop count and also sleep mode should be activated when they are not been used for transmission. Besides that underwater sensors are easily effected by and are prone to failures due to corrosive environment. These are some of the major challenges in underwater networks.

II. COMMUNICATION ARCHITECTURE OF UNDERWATER ACOUSTIC SENSOR NETWORK

Underwater acoustic sensor networks use the following communication architectures:

Two Dimensional Underwater Acoustic Sensor Network:

Static two dimension underwater sensor network: This consists of sensor nodes which are connected to the bottom of the sea as shown in the figure 1. In this type of network, the node or sensor movement is restricted to the movement of the chain which is attached to the bottom of the sea. These sensor nodes can send the data from the sea bottom to surface station through underwater sink via wireless acoustic links. Underwater sink is like a float to communicate with the surface station. It consists of acoustic transceiver to communicate with sensor nodes and also to convey data to a surface station. Underwater sink is used to configure sensor nodes due to dynamic environment.

Three Dimensional Underwater Acoustic Sensor Network:

Static three dimensional underwater acoustic sensor networks: This includes acoustic sensors with additional degree of freedom i.e. their depth can be altered. The major difference between two and three dimensional underwater acoustic networks is the floating of sensor nodes at different levels to monitor the underwater environment. Sensor nodes are connected to bottom of the ocean with the help of a buoy. The buoy and controller are used to regulate the movement of sensor node in underwater environment by altering the wire-length attached to the buoy. These sensor nodes convey depth information to check connectivity between sensor nodes and verify the connection between sensor nodes and surface station.

Three Dimensional Underwater Acoustic Sensor Network with Autonomous Underwater Vehicles:

The 3-D underwater acoustic networks with autonomous Underwater Vehicles: These networks include both fixed and mobile systems. Fixed system is composed of anchored sensor nodes with limited coverage and the mobile system consists of autonomous underwater vehicles (AUVs) which can move randomly in underwater environment to collect and transmit information to the base station. The integration of sensor networks with mobile AUVs and underwater network coordination algorithm needs further investigation. The most important goal of Autonomous vehicle is to depend on primary intelligence rather than waiting for communication from offshore system. Algorithms must be developed for movement of autonomous vehicles. Energy efficient control of AUV's by the help of solar powered battery is an important research area which needs to be investigated further.

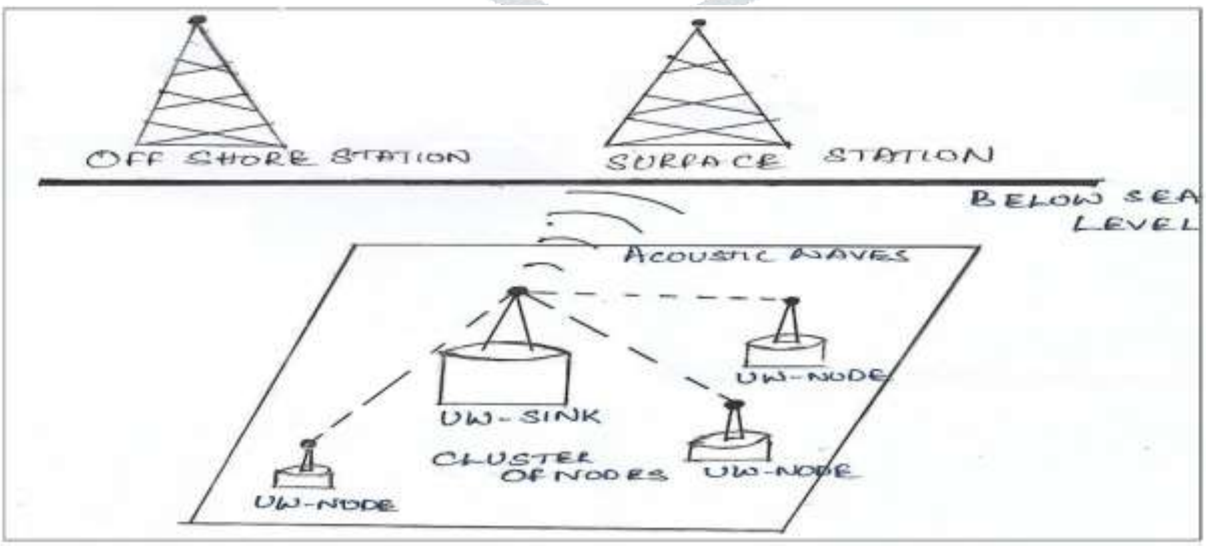

Fig. 1. Architecture for two dimensional underwater acoustic sensor networks

III. CHALLENGES ASSOCIATED WITH UNDERWATER ACOUSTIC COMMUNICATION

Underwater acoustic communication network link are classified according to the distance they travel as very long. long, medium, short and very short. Table I shows relation between bandwidth of acoustic channel for different ranges the acoustic signal can travel.

Description	Range [km]	Bandwidth [kHz]
Very long	1000 Km	<1 kHz
Long	10 km –100 Km	2–5 kHz
Medium	1–10 Km	10 < kHz
Short	0.1 km –1 km	20–50 kHz
Very Short	<0.1 km	>100 kHz

Table 1: Available Bandwidth for different Ranges

Underwater acoustic communication is effected by frequency, sound speed, loss of data as they travel (Path Loss), ambient noise, Doppler spread, refraction, scattering and propagation delay.

1) Frequency and Range: The range or the distance varies with bandwidth or frequency as acoustic absorption varies with frequency. Different bandwidths are available for different ranges as shown in table 1. Acoustic absorption also depends on temperature, depth, Salinity and pH in addition to frequency. Therefore the available bandwidth for acoustic communication is limited.

The sound wave expands as a spherical wave in a homogeneous medium as shown in Fig. 2. The acoustic intensity I is inversely proportional to the square of the distance travelled. This is given by

$$I \propto 1/R^2$$

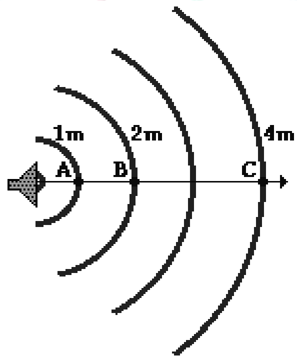

Fig.2. Spherical spread of sound wave

The attenuation of the acoustic signal varies with frequency and range. From the table 1 it is clear that attenuation of the signal is more at higher frequencies.

2) Sound Speed: The propagation speed of sound in the underwater networks is around 1500 m/s which is five times less than that of radio channel. This large delay leads to reduction in efficiency of the system by a large factor. The delay in acoustic signal can a major impact on protocol designing, as this can hinder the process of calculating or estimating the round trip time (RTT) accurately. Since RTT is a key measure in the design of communication protocols. Also water has higher viscosity, heat capacity, and conductivity of sound waves when compared to air. These properties of water make the movement of sound more complex particularly in ocean. Sound speed plays an important role in designing efficient communication protocols. The speed of sound in underwater environment is more difficult to find out as it gets affected by temperature, diffused impurities (usually salinity), pressure due to height (depth) and density.

3) Temperature: Sound speed gets affected by temperature. Sound travels faster at higher temperature as the energy associated with molecules increases with increase in temperature leading to faster molecular vibration when compared to their vibration at lower temperatures. Speed of sound is affected by three variables such as temperature, salinity and pressure (depth). Sound speed can then be approximated as follows:

$$C = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016D \quad \text{--- (Equation 1)}$$

where T is temperature (ºC), S is salinity in parts per thousand and D indicates depth in meters. This equation 1 is valid for all depths upto 800m and for temperatures between -2 ºC and 30 ºC and for salinities between 25 and 40%. Therefore sound speed increases by about 4m/s per degree change in temperature, 1.5 m/s per 100m depth increment and 1m/s for a salinity increase of 1%.

4) Hydrostatic pressure or the fluid pressure increases proportionally with respect to surface depth (depth measured from the surface) because of the increase in pressure (due to weight) of fluid exerting downward from above. Hydrostatic force acting on the water affects the direction of acoustic signals.

5) Density: Dynamic environment of ocean may lead to difference in density across different parts of ocean. The speed of sound gets affected due to difference in density at different points of the channel. Sound travels faster in rarer environment when compared to denser one as it takes more energy to vibrate larger molecules when compared to smaller ones.

6) Path loss: This occurs due to transformation of sound energy into heat energy. As sound waves travel under water, the energy gets converted and absorbed by water in the form of heat. In simple words, sound energy gets transformed to heat energy. This leads to loss of acoustic signal as it travels, which is referred as path loss. The attenuation increases with increase in distance and frequency.

The underwater channel is defined by the path-loss formula:

$$TL(d, f) = \chi \cdot \log(d) + \alpha(f) \cdot d + A \quad \text{--- Equation (2)}$$

The underwater acoustic signal propagation has three components. The first component describes attenuation based on travelled distance (d) and the term χ relates to geometric spreading. This spreading depends on water depth. In shallow waters, acoustic waves spread cylindrically. Thereby higher amount of the signal is preserved. Usually $\chi = 10$ for shallow water environment. On the other hand, in deep water, spherical spreading takes place which leads to more attenuation with increasing distance For deep water, $\chi = 20$.

The second term in the equation i.e. $\alpha(f)$ (medium absorption) is a function of the frequency f. Finally, the last component A[dB] accounts for degradation of the intensity of the sound wave due to multiple path propagation. The value is high for shallow-water horizontal links as the effect of multipath propagation in underwater is more in shallow water links.

7) Noise: Man-made noise and ambient noise due to industrial, shipping, aquatic and seismic activity can affect the propagation of sound. Machinery noise due to noise from pumps, shipping and logistic activities has their effect on acoustic communication. To eliminate the noise from the actual signal, a threshold limit (detection threshold) is introduced. The intensity of the signal above detection threshold is considered as actual signal. If the detection threshold is selected a high value then only strong targets will exceed the threshold level and get detected. False alarms can be avoided by setting a high threshold level. However, when threshold is set at low level, weaker targets gets detected and number of “fake alarms” will increase.

8) Multi-path: Multi-path propagation of acoustic waves leads to intersymbol interference (ISI). ISI causes distortion of signal due to interference from multiple paths of the signal. One symbol interferes with many other symbols due to multi-path propagation leading to distortion. Vertical channels are affected by time dispersion whereas horizontal channels are affected by spreading of acoustic waves into multiple paths. The extent of spreading depends on depth and distance between transmitter and receiver. Acoustic underwater channel can be either shallow water channel or deep water channel.

The **shallow-water channel** is affected by multiple paths either from rays being reflected by the sea bottom or surface as shown in figure 3. Ray also bends due to variation of sound speed with respect to depth. Acoustic communication in shallow water takes three paths as shown in figure 3.

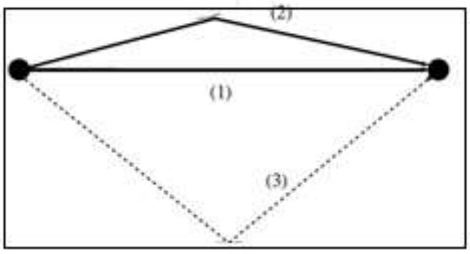

Fig.3. Multi-path acoustic communication in shallow-water channel

It can be a (1) Straight path (2) reflection from surface and (3) reflection from bottom as shown in the figure 3.The reflections from the surface and bottom of the sea are called as macro-multipath. The waves reflected from the surface and the sea bottoms are responsible for introducing disturbances into received signals. These time-dependent variations or fluctuations are called as micro-multipath. In shallow-water communication, the wireless channel is modeled as a multi-ray Rayleigh fading channel. The quality of these rays at the receiver governs the success of the communication.

The **deep-water acoustic channel** is not severely affected by multiple paths when compared to shallow water acoustic channel. In the case of deep water acoustic channel a higher attenuation is present due to the spherical spreading of the acoustic signal.

9) Speed of the Sound: Another parameter that can affect acoustic communication is **speed of sound.** As the acoustic signals travel from one point to other, they bend towards the region of slower sound speed. The propagation speed of sound signals in underwater environment depends on the depth and temperature. Therefore the propagation path of the sound wave depends on the location of the transmitter and also on the thermal structure of the particular medium.

The four types of thermal structures are isothermal gradient, negative gradient, positive gradient, and negative gradient over positive. In isothermal environment, water temperature is remains constant at the surface and thereby decreases slowly below a certain depth. This causes the signal to remain straight upto uniform temperature level and then it splits as shown in Figure 4. In negative gradient thermal structure the water temperature decreases with increasing depth. This causes the acoustic signals to bend towards region of slower speed as shown in Figure 4. The opposite is true for positive gradient as shown in Figure 4, where acoustic signals bend towards the region with higher speed. For the negative gradient over positive thermal structure, the temperature gradient also changes with depth. In this case, the acoustic signal first moves lower speed and then towards higher speed region as shown in Figure 4. Due to the unique propagation characteristics of acoustic signals in under water environment, communication regions as well as shadow zones are formed.

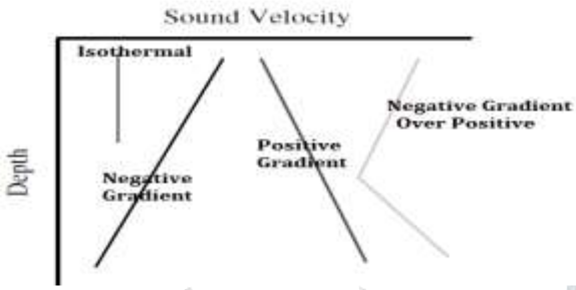

Fig.4. Sound propagation in different thermal structures with respect to depth

10) Doppler Spread: The Doppler frequency spread can be significant in underwater acoustic channel. Doppler frequency shift is mainly due to motion of the source or motion o the observer or it can be due to motion of the medium which leads to which leads to either increase or decrease in frequency. Doppler spread or shift in frequency can lead to a decrease in the performance of digital communications. Transmission of acoustic signals at high data rate may cause adjacent symbols to interfere at the receiver leading to requirement of high-end signal processing device that deals with generated intersymbol interference (ISI).

IV. ARCHITECTURE OF UNDERWATER ACOUSTIC SENSOR NODE

Depending on the unique problems faced by underwater environment, different types of underwater sensors are developed. The typical architecture of underwater acoustic sensor is as shown in Figure 5.

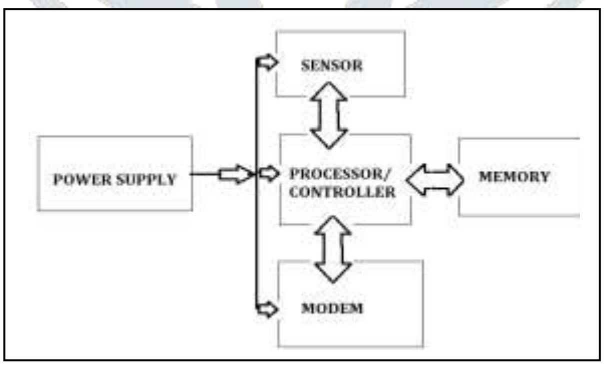

Fig.5. architecture of underwater sensor node

The architecture of an underwater acoustic sensor node consists of a sensor interfaced to a main processor/controller through sensor interface channel. The processor on receiving the data processes it, stores in the memory chip and sends the data to the sink node or other nodes using acoustic modem. The acoustic modem consists of acoustic transmitter and receiver. The entire electronic circuit is placed in a waterproof frame (PVC housing).

These sensors are used to measure different parameters which include temperature, density, acidity and conductivity of water. These are also used for measurement of oxygen and hydrogen content present in the water. Harmful content present in the water can also be measured. Examples of underwater sensors include Examples of underwater sensors are Aquacomm underwater modem and LinkQuest underwater acoustic modem.

V. INTERNODAL UNDERWATER ACOUSTIC COMMUNICATION

Two nodes communicate with each other in acoustic medium (sound). Therefore distance between two nodes is calculated basing on the sonar equation. Sonar equation is a way of finding the signal to noise for the received acoustic signal. Here the signal level indicates the intensity of the acoustic signal. The intensity of an acoustic wave is the amount of energy transmitted per unit time through a unit area in a specified direction.

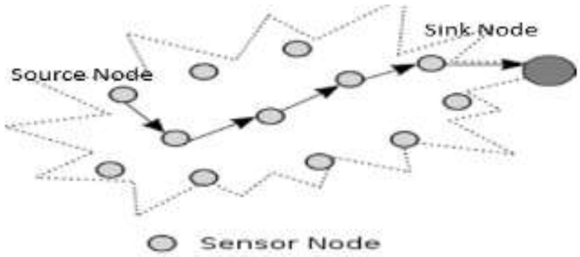

Fig. 6. Source Node to Sink Node Communication Link

The rate of energy is called as power, and intensity is therefore the amount of power transferred through a unit area in a specified direction. The sound intensity level, I, is defined as 10 multiplied by the logarithm of the ratio of the intensity of an acoustic wave to intensity of reference signal. Underwater microphones such as hydrophones measure the pressure of sound wave because the intensity of sound wave is proportional to the square of its pressure p:

$$I = (P^2 / \acute{\rho}C)$$

where ρ is the density of medium (acoustic Signal movement) and c is the speed of sound). The sonar equation measures the entry signal level at the source, loss due to spreading of sound and attenuation loss as the sound pulse travels from the one node to the other node. The background noise at the receiver (Noise Level) and the receiver characteristics (array gain AG). These terms are added to sonar equation in order to get final sonar equation. The source node transmits a signal with a source level SL. The sound becomes weaker as it travels from one node to the other node (target node) due to spreading and absorption. The total reduction in signal intensity is called the transmission loss TL, given in decibels. The sound intensity at the target node is then (SL -TL) decibels.

Intensity at target node is given by (decibels) =

(SL – TL) – (NL-AG) --- Sonar equation

Once the target node receives the signal from source node, it sends an acknowledgement signal to the source node or the preceding node. In this way signal gets transmitted from one node to the other. Efficient underwater acoustic communication is the need of the hour on the backdrop of different challenges being faced by underwater acoustic sensors networks.

Networking challenges depends on the application requirements. For example, surveillance application, disaster prevention require less response time and thus networking protocols that provide time bound delivery are required so that connection can be re-established as soon as it is lost (dynamical rerouting). In some applications response time and data to be sent can be more. In such a scenario, protocols can be developed to ensure data is delivered by using save and forward method with a long or variable delay. These are called as delay tolerant applications. In order to have faster communication between source node and sink node, proper routing protocols have to be designed.

VI. ROUTING PROTOCOLS FOR UNDERWATER COMMUNICATION

Efficient routing protocols have to be designed to overcome different challenges being faced in underwater environment. In Underwater acoustic sensor networks, routing means to determine which path should data packets follow from source node to collects information about physical phenomenon to the onshore sink node. Intensive research is going on in the field of routing protocols for ad hoc wireless sensor networks. Due to unique and different nature of the underwater environment, there are many issues and problems with respect to the suitability and acceptability of the solutions for Underwater Acoustic Networks. The existing routing protocols are mainly divided into three categories. They are proactive, reactive, and geographical routing protocols.

Proactive protocols: These protocols maintain updated routing information all the time to reduce the time required for finding the optimum route. This helps in decreasing the time-delay in conveying information from source node to sink node. Maintaining updated routing information is made possible by broadcasting control packets containing routing information (e.g., direction and distance between two nodes). These protocols leads to a large signaling overhead to establish routes for the first time and also each time there is change in network topology due to mobility of nodes or node failure since updated topology information of nodes has to be broadcasted to all other nodes in the network. This is how a path is established from source to sink node through other nodes. Therefore, proactive protocols are not suitable for underwater networks. Examples Include: Destination sequenced distance vector (DSDV) routing protocol.

Reactive protocols: A node initiates a route discovery process only when it is required to send the information. Once a route established between sink and source node, the routing information is maintained by route maintenance procedure. These protocols leads to higher latency or time delay as routing information is not maintained beforehand. In this type of protocol also flooding of control packets takes place for routing information. Thus, both proactive and reactive protocols incur excessive signaling overhead. Example: Ad-Hoc on demand distance vector (AODV).

Geographical Routing Protocols: These protocols establish source-destination paths by taking advantage of localization information, i.e. each node selects its next node basing on the position of the neighboring nodes and that of the sink node. The main problem with this routing protocol is in finding accurate localization information in underwater environment with limited energy expenditure. Mobility of nodes also throws a challenge in finding location information about nodes. In addition to that, global positioning system (GPS) receivers used in terrestrial networks cannot be employed in underwater environment. Example include Partial topology knowledge forwarding (PTKF) routing protocol.

Thus, routing schemes that jointly minimize the signaling overhead and the latency need to be developed. Furthermore, routing schemes needs to be developed for 3D underwater environment. In the case of 3D, the effect of currents should also be taken into account as they can modify the position of sensor nodes. This can cause connectivity holes leading to loss of data, especially when ocean column monitoring is performed in deep waters. Many routing protocols have been developed to overcome different problems that are encountered in underwater acoustic sensors network such as energy efficiency, transmission latency, connectivity holes to name a few. Existing routing protocols have been studied and compared on the basis of different parameters.

Hop-by-Hop Dynamic Addressing Based (H2- DAB) routing protocol [13]: The problem of node mobility is taken into account while designing this routing protocol. Each sensor node is given a routable address that has two parts: node ID and hop ID. Even though some nodes come and leave the network due to mobile environment, they can obtain their routable address without static configuration. The address of the node indicates the number of hops data has to be covered to reach the water surface. However, routable address table needs to be updated in a time bound manner, which needs further research.

In Depth-Based Routing (DBR) protocol [7] each node takes the decision of forwarding packets to the next node basing on its depth and that of the previous sender. However, there is a possibility of multiple nodes forwarding the same leading to packet collisions, transmission delay and energy consumption. In order to overcome the problem of packet collisions, **Delay-Sensitive Depth-Based Routing (DSDBR) protocol** is proposed. In this protocol holding time is employed to minimize the delay. Holding time is the time for which the data packets can be kept on the sensor nodes before they get transmitted to the next node. DBR protocol is further transformed later into **Energy Efficient Depth Based Routing protocol (EEDBR)** where along with depth, residual energy of the nodes are considered for selection of next hop. However, for efficient transmission, depth information and residual energy of the nodes have to be updated.

Energy optimized Path Unaware Layered Routing Protocol (E-PULRP) [9]: In this we have two phases, layering phase and the communication phase. In the layering phase, different layers are constructed basing on the energy levels of sensor nodes. In the communication phase, a relay node is chosen from each layer basing on their distance from sink node. In order to increase the lifetime of sensor nodes, sleep mode is activated for non communicating sensor nodes to save energy. Due to dynamic underwater environment, the nodes may not be static and thereby affects the performance of this routing protocol in underwater environment.

QELAR (A Machine-Learning-Based Adaptive Routing Protocol for Energy-Efficient and Lifetime-Extended) [8] uses a Q-learning algorithm to transmit packets with minimum cost. Basing on the algorithm, the node with the highest reward is selected for forwarding packets. By using this technique we can reduce overload in the network and also balance the work load among different sensor nodes. But each sensor node has to store more information for calculation of reward function.

Adaptive Routing Protocol (ARP) [11] is based on assigning priority to the data packets. In order to reduce the time delay during transmission and to save energy, this ARP protocol has been introduced. Different priorities are assigned to data packets basing on the emergency level, residual time spent in the network and also it checks for node status and residual energy of a node before it transmits the data packets.

Link-state based Adaptive Feedback Routing (LAFR) [10] is another protocol where the asymmetry of communication link is considered for data transmission. A sensor node can easily transmit data packets directly, if the source node and its neighbor node are joined by a symmetric link. This saves lot of energy consumption for routing process. In addition to this, a time-bound priority forwarding mechanism is used for prevent broadcasting of routing request packets continuously.

Mobicast Routing Protocol (MRP) [12] is proposed for underwater networks with a dynamic sink and underwater vehicle. Sensor nodes are placed in a 3-D zone. The sensor nodes that are collecting data in 3D zone are required to remain awake and transmit data to sink, while the other nodes can sleep. MRP protocol has two major tasks. The first is to collect data within a 3-D zone and the second is to wake up the sensor nodes in the next 3-D zone. MRP protocol also takes care of holes created by movement of sensor nodes due to ocean currents.

Based on the survey of existing underwater routing protocols, we can tell that the existing routing protocols do not solve all the networking problems in the underwater environment. They also do not consider security problems due to malicious attacks which is the latest research area in underwater networks.

VII. CONCLUSION

In this paper, an attempt has been made to understand the underwater environment and its challenges with reference to underwater acoustic sensor networks. The effect of different parameters like hydrostatic pressure, density and temperature on underwater acoustic communication has been discussed. The internal architecture of wireless sensor node and the challenges posed by the underwater sensor network in designing sensor nodes have been discussed. In this paper, we observed different challenges for efficient communication in underwater acoustic networks. We understood the difficulties in designing routing solutions for underwater networks. Routing protocols is one of the major research areas in underwater networks. Many routing protocols have been proposed for underwater networks. In this paper, a detailed survey of underwater routing protocols has been done. The problems in the design of routing protocols include energy efficiency, latency, hole bypassing, multi-path propagation and many more which are yet to be solved. Therefore, further work should be done and propose new solutions to design a better routing protocol.

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