An Overview of Underwater Sensor Networks

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***Abstract*—It is becoming clear that underwater sensor networks are needed to predict natural disasters, provide scientist research for marine life exploration, and to advance military capabilities. These underwater sensor networks pose great challenges to our existing technologies used in terrestrial sensor networks, mainly due to the acoustic waves used in water. These waves behave differently than the radio waves on land. The purposes of this research paper is to provide a better understanding of an underwater sensor network architecture, basic characteristic, applications, and examine the propagation limitations of acoustic communication. We also provide an overview of modulations and medium access controls.**

Keywords-Underwater sensor; architecture; applications; propagation; modulation

I. Introduction

Underwater Sensor Networks' (UWSN) are made up of many sensor nodes and Autonomous Underwater Vehicles (AUVs). Together, these sensor nodes and AUVs allow researchers and the military to actively monitor the ocean. Underwater sensor networks make it possible to conduct search missions, record climate changes, provide pollution control, study marine life, conduct survey missions, tactical surveillance, and predict natural disturbances in the ocean. There has been an increased interest in building UWSN due to the fact that, these networks have the ability to monitor, investigate, and track underwater occurrences that are important to our national security and off shore exploration. Many characteristics of these networks make their construction challenging, and difficult to implement. These characteristics include: limited bandwidth capacity, high error probability, large propagation delays, fouling, corrosion, high bit rate errors, limited battery power, and temporary losses of connectivity. Another key characteristic is that, the sensor nodes and autonomous underwater vehicles must have the capability to self-configure themselves. The devices should be able to coordinate their configurations, location information, and movement information with each other. Data must also be sent back to an on-shore station. The technology that enables the application is wireless underwater acoustic networking. Underwater communications is not new. In 1945, there was a need to communicate with submarines in the United States. The development of an underwater telephone was the solution, as outlined by Akyildiz et al. [1]. However, underwater networking really has not been extensively explored. Underwater sensor networks use acoustic communications based on acoustic wireless communication. Radio waves can travel long distances underwater, but must travel along very low frequencies. The frequency range typically used is 30-300 Hz. This frequency range requires extraordinary transmission power and very large antennas.

In this paper, we discuss the aspects of underwater sensor networks that create challenges in design, types of applications, underwater sensor architecture, modulation, and the available medium access control protocols.

II. Applications

Underwater sensor networks are needed for several applications. The military can use this technology for mine reconnaissance. Mine reconnaissance is when autonomous underwater vehicles equipped with optical sensors perform assessments on objects that appear to be mines and detect whether they are in fact, mine like materials. They also use the networks for distributed tactical surveillance. In this application, sensors are used along with AUVs that work together to monitor an area for targeting, intrusion detection, surveillance, submarine warfare, and reconnaissance. A surveillance system is able to detect divers, submarines, and other vehicles based on data, sensors collect. These systems have higher accuracy rates than typical sonar systems.

There are also many geological applications that make use of an underwater sensor network. Sensor networks can monitor seismic activity along the ocean floor to measure earthquakes and predict an approaching tsunami. This data allows coastal areas to be notified and warned in time to evacuate the immediate danger area. Environmental monitoring applications allows for the detection of pollution, and how it is affecting marine life. The data can monitor chemical, biological, and even nuclear pollution in any body of water giving a more sophisticated analysis of water quality as outlined by Heidemann et al. [5].

Sensors can also monitor winds and ocean currents to predict the weather in a more reliable fashion. Climate change can also be monitored and studied along with the human effects on ecosystems, and biological tracking of fish. Applications to assist navigation can be useful to boat operators in shallow waters to determine potentially dangerous objects under water. Assisted navigation applications can also be used to find sunken boats and wreckage. Autonomous Underwater Vehicles (AUVs) are useful in many applications because they do not require

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cables, tethers, or remote control. These devices are inexpensive and can reach any depth in the ocean and can be used in environmental monitoring and oceanography applications. One of the most common AUVs is small submarines armed with many sensors.

III. Architecture

There are two types of architectures including: two-dimensional (see Fig. 1) architecture and three-dimensional architecture (see Fig. 2) as outlined in [1]. Static two-dimensional are used for environmental monitoring where sensor nodes are anchored to the ocean floor. These nodes are interconnected to underwater sinks. The sinks are in charge of relaying information from underwater to the surface station. They have a vertical acoustic transceiver and a horizontal acoustic transceiver. Horizontal transceivers communicate directly to the sensor nodes to send command, configurations, and collect monitored data. The vertical transceivers relay the data back to the surface. The on-shore station also has a transceiver that will handle multiple transmissions from the sinks. The sinks can be connected with underwater sensors by either a direct link or by a multi hop path. The easiest way to connect to the sensors is through a direct link, but is most likely not the most energy efficient way to connect. By using direct links, the throughput is also reduced due to acoustic interference. The acoustic interference comes from the high transmission power being used. The key difference in multi hop systems is that the information is relayed through intermediate sensors until it reaches the sink. This increases the network capacity and saves energy, which are two important aspects in underwater sensor networks.

The three-dimensional architecture is normally used when you want to identify or observe happenings that cannot be looked at with the sensor nodes attached to the ocean floor. In these networks, the sensor nodes float at various depths to observe any occurring phenomenon. These sensors could be placed on buoys with varying wire lengths to achieve different depths. Although this would be the easiest approach, floating nodes on buoys allows for problems involving tampering. For example, if the military is carrying out a surveillance of an enemy the nodes could be detected and disabled easily. The nodes are more susceptible to weather conditions, and multiple buoys could confuse boaters navigating the open waters. These reasons make this approach not very desirable.

Another approach would be to fasten nodes to the ocean bed. Once anchored, floating devices are attached that can be filled with air to achieve a variation in depth placement. The depth is determined by the wire length as in the first approach, but the nodes here have their own electric motors that can change the wire length on demand. There is still a disadvantage with this approach as well. Ocean currents could interfere with the system’s ability to maintain the desired depths [1].

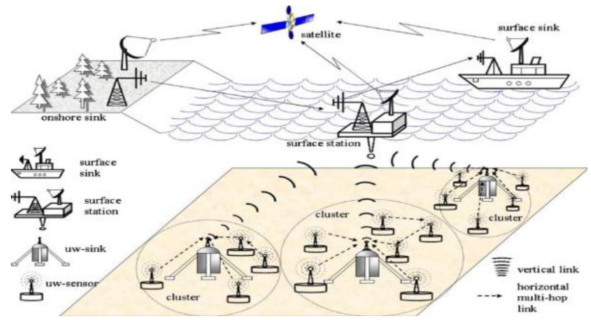

Figure 1. Architecture for 2D underwater sensor networks. [1]

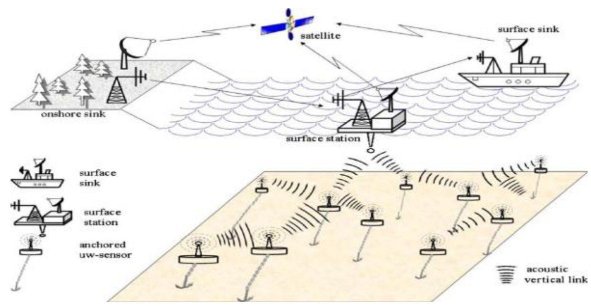

Figure 2. Architecture for 3D underwater sensor networks.[1]

IV. Autonomous Underwater Vehicles

AUVs are important to the network design. One objective for them is to become less dependent of on-shore communication and move toward relying solely on local intelligence. Recovering AUVs to recharge their batteries can be a cumbersome task; therefore, solar systems seem to be a viable option. Solar energy will increase the AUVs overall lifetime and they will be able to gather data continuously for several months before any human intervention is needed. Two kinds of AUVs used in explorations are called drifters and gliders. These are oceanographic instruments that do not need the same level of sophistication as small submarines. Drifters work with the current. They have the capability to move vertically, but drift along with the current. Their main purpose is to take various measurements at different preset depths. Gliders are powered by a battery and use hydraulic pumps create changes in their buoyancy to move through the water. They are equipped with a GPS device that allows them to be located once they climb to the surface. Typically, these devices can only operate for a few weeks to a few months, and can reach depths of 200 meters to 1500 meters. Gliders move very slowly through the water which allows them to conserve battery power and increase their lifetime [1].

V. Unmanned Underwater Vehicles

The use of Unmanned Underwater Vehicles (UUV) is important to improve system efficiency. The Department of Defense, Homeland Security and the military are extremely interested in the capabilities and advantages that unmanned

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underwater vehicles possess. The military has conducted several test deployments of this type of vehicle as outlined by Garreiro et al. [4]. Some of the test deployments included UUVs are: Remote Environmental Measuring Units (REMUS) [4], Mid-sized Autonomous Research Vehicle (MARV) [14], 21" Unmanned Underwater Vehicles (21UUV) [4], and Manta Test Vehicle (MTV) [4]. REMUS was 7.5 inches in diameter and was deployed for testing hundreds of times. It used acoustic communications with both oceanographic and chemical sensors. MARV is a mid-sized autonomous research vehicle that was 12.75 inches in diameter. It demonstrated various technologies under thruster based hover payload with low speed control. 21UUV is 21 inches in diameter and has been tested in the water over one hundred times. This vehicle demonstrated vision based navigation, photo mosaic, and side scan sonar imagery. This device was used for autonomous controller experiments where it was a test bed and weapon launch using MTV. MTV is a manta test vehicle that was tested in the water over ninety times for unmanned weapon launches. This vehicle had advanced network communications with ISR suites including RADINT, SIGINT, Optics, and IR. The military branch testing these UUVs is the NAVY. The military would like to have a family of not only unmanned underwater vehicles but also just unmanned sensor vehicles. These vehicles would include advanced sensors such as smart skins and Nano-sensors that work in conjunction with distributed underwater networks. The potential advanced payloads would allow for attacks to the enemy without being seen. Missile launching would be executed from underwater. Unmanned underwater vehicles might just be the weapons of the future, providing the military with high energy lasers and advanced weaponry [4].

The one thing that slows down the development of these weapons is the guidance laws that must be followed. These laws require vehicles to have onboard navigation guidance controls that enable vehicles to work with each other to achieve proper positions and orientation. Missile guidance requires line-of-sight guidance laws, command-to-line-of-sight guidance laws, proportional navigation guidance laws, and optimal guidance laws. The majority of the missile laws are already implemented in traditional missile weapon technologies; however, underwater unmanned vehicles must be programmed and tested thoroughly before building the weapons of the future as outlined by Sutton et al. [9].

VI. MODULATION

The electromagnetic spectrum controls all communications on land, because telecommunication companies have to constantly provide ways to communicate over long distances. This is made possible through radio and optical systems. These systems also allow for high bandwidth capacity on land, whether the power is high or low. In the physical layer of underwater sensor networks, the communication approach used is acoustic. Acoustic waves are the best choice for underwater systems, mainly because electromagnetic frequencies are diffused by the water. The acoustic communication system allows for better communication beyond ten meters as outlined in [5].

Acoustic communications have to deal with the network performance limits and poor bandwidth efficiency. To address these issues modulation schemes are used. The best modulation approach to achieve more bandwidth efficiency is Frequency Shift Keying (FSK). This approach is resistant to channel variations because carrier frequencies are chosen using information bits. At the next stage, measured power is compared at different frequency levels by the receiver to determine what was sent. Therefore, channel estimation is not needed because the receiver is using just energy detection. A disadvantage of frequency key shifting is the use of guard bands. Guard bands are inserted between the frequencies to prevent frequency spreading. Time spreading also causes interference, and guard intervals must be placed between consecutive symbol communications to promote channel clearing. These two introductions of guard bands and intervals slow down the data rate to an extremely low level as outlined in [1].

In order to use FSK advanced approaches would need to be added to improve the low data rate. One approach that could be implemented if the bandwidth is not under any constraints, would be frequency hopped FSK. Frequency hopped FSK removes the requirement of guard intervals to promote channel clearing. Another method of modulation that has had very little success is called multi-carrier modulation. This type of modulation divides the amount of bandwidth that is available into overlapping sub bands. This makes the duration of the waveform longer for each symbol. The sub-bands allow the system receiver to disregard inter symbol interference making channel equalization at the receiver simpler. This simplification has prompted attempts to integrate Orthogonal Frequency Division Multiplexing (OFDM) into the underwater channels. The problem with this type of multiplexing is that the channels themselves have large Doppler spreads allowing for a substantial introduction of interference in the subcarriers [5]. Phase coherent modulation includes Quadrature Amplitude Modulation (QAM) [12] and Phase Shift Keying (PSK) [12] is direct transmissions that can be used to promote high data rate communication in underwater networks, but also introduces inter symbol interference. The interference must be addressed at the receiving end of communication.

There are two modulation approaches that are promising for underwater sensor networks. These methods include: Code Division Multiple Access (CDMA) and Multi-Input Multi-Output (MIMO) techniques. CDMA is an up and coming technology that is important in acoustic networks. This is because this method allows for random, overlapping access to communication channels that are being shared in the network. CDMA is promising as a viable modulation approach to underwater sensor networks. Multi-input multi-output approaches require a system of multiple transmitters and receivers to increase channel capacities linearly. The degree in which channel capacities become linear depends on how many transmitters and receivers are added to the system. This technique looks to be extremely promising for underwater acoustic communication as outlined by Manjula et al. [6].

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VII. PROPAGATION

Propagation in underwater sensor networks poses a major challenge for technologies we currently use in terrestrial sensor networks. Acoustic waves used for underwater networks have a lower loss than the traditional radio waves used in other sensor networks. The lower losses of these waves make them more suitable for underwater applications than radio waves. Acoustic waves travel at five orders of magnitude slower than radio waves presenting greater challenges that must be overcome with algorithms, protocols, and node placement [6].

Propagation is affected by several factors underwater. Hereafter we describe some of these factors influencing propagation. When data travels from one place to another, it will always experience some level of power loss. This power loss is called attenuation. In underwater acoustic channels, propagation delay limits the available range and frequency at which the system can function. When greater distances are needed to be covered by the system or if higher frequencies must be used will have an increase in attenuation. Attenuation is also caused when the ocean is rough at the propagation medium constraints.

Surface-bottom reflection and refraction occurs when the depth changes the speed at which the data is being transferred. Surface-bottom reflection and refraction is constantly present in underwater networks because the ocean's velocity changes frequently due to storms, tides, and waves. These changes create different levels of refraction that must be dealt with, at all levels of the system, but particularly in deeper waters [5]. This is especially true in large scale systems. Doppler effects are also created due to different levels of directional motion that introduce long delay spreads and phase distortion.

Noise is another factor in underwater sensor networks that effects the propagation. The propagation medium in these networks is constrained by the ocean floor and the surface. These constraints cause multipath propagation where echoes are created from unwanted reflections. The echoes appear as signal burst or as signal transmission replications. Multipath propagation allows each of the components throughout the underwater sensor network to potentially exhibit different forms and levels of attenuation as outlined in [5]. Man-made noise caused by boats, power plants, and oil pumps along with noise created from shipping activity can create propagation delays especially where there is lots of boating activity. Ambient noise is created by the natural occurrences in the ocean. Tides, waves, rain, wind, and seismic activity is categorized as this type of noise.

Acoustic waves carry noise farther than radio waves making noise, a more severe problem when dealing with acoustic communication. As one can see the variability of propagation requires the underwater sensor network to be robust in many areas, where in radio communication, the variations are more localized and easier to address. There are several different propagation models with different degrees of complexity and accuracy to simulate and analyze an underwater wireless sensor network. Designing an efficient and reliable communication channel in underwater environment is not an easy task because of speed of acoustic signal, propagation delay, multipath interferences, path loss due to higher frequency, and high bit error rate due to phase and magnitude fluctuations. Absorption is also increased with the range, which causes the increasing drop of SNR when the range increases. Figure 3 shows the Signal-to-Noise Ratio (SNR) increase with distance [11].

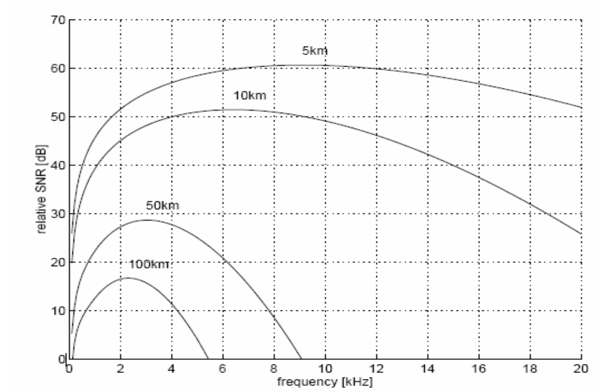

Figure 3. SNR vs. frequency and range for undersea. [11]

VIII. MEDIUM ACCESS CONTROL

Medium Access Control (MAC) takes place in the data link layer and manages access to the underwater networks acoustic communication. To keep the network performance at its best MAC protocols must be used. The main objective of MAC protocols is to prevent any collisions that could occur. These protocols also manage network throughput, scalability, adaptability, latency, and energy consumption (efficiency) as outlined by Pompili et al. [8]. Medium access control can either be contention free or contention based protocols. The contention free approach allocates different time slots, frequencies, or codes to all of the system nodes to avoid collisions in the physical layer. In contention based approaches the nodes must compete with one another to use the medium. This is all handled on a demand bases, and the protocol must work to keep overhead down while still preventing any form of collision as outlined by Otnes [7]. Some contention free MAC protocols include Frequency Division Multiple Access (FDMA) [13], Time Division Multiple Access (TDMA) [13], and Code Division Multiple Access (CDMA) [13]. FDMA divides the available bandwidth into several frequency bands and then places guard bands between them. The individual bands are assigned to each station where they can send data. Once these bands are assigned, they remain those stations until the end of communication. Station interference is handled with a band pass filter and guard bands that confine and separate the transmitter frequencies. FDMA is ideally used with stream data because it identifies preset frequency bands and uses them for the entire length of communication [3].

In an underwater sensor network, FDMA would allow each individual node to communicate the remaining nodes simultaneously without interference with each other. However, because acoustic communication has a limited bandwidth capacity and multipath propagation, it creates spectral nulls. If the underwater network has several nodes it will require a very narrow frequency band for each node. Operating the system in this way produces extreme risks of complete fading to some of the nodes. For this reason FDMA is not considered a viable option for underwater networks according to [7]. FDMA could very well be used along with clusters using higher frequency bands to create a usable hybrid system. TDMA uses only one channel that is shared between all of the nodes in the system. This is accomplished by timesharing. Frames, or time-intervals, are split up into fixed length slots where each node in the system is assigned a slot [10]. The node can only transmit during its allocated time, and then wait until the frame is repeated cyclically back to their time slot before transmitting again. In this approach all of the systems nodes have to know when their time slot begins and ends which adds additional propagation delay into the system. These added delays can be compensated by the use of guard times, but in underwater systems where propagation delays are already high this is not ideal. TDMA does not allow the nodes to transmit data simultaneously, so in order to handle synchronization it normally adds preamble bits to the beginning of each slot [3]. The addition of guard times and preamble bits will also degrade the efficiency to some extent [7]. CDMA is typically used in cellular technologies. It is a spread spectrum technology that takes multiple telephone conversations and attaches a certain code that only the sender and receiver understand. It then cuts the information into bits and transfers them to the receiver to reconstruct [2]. CDMA in underwater sensor networks work in much the same way. They also use binary (bits) to modulate the data with the same speed spectrum concept. This MAC technology is a very promising technique for acoustic communication. CDMA's advantage over FDMA is its resistance to node fading, because the frequency band is used by the entire system of nodes. This is because each node uses a unique code with low cross-correlation that allows all of the nodes to send and receive data at the same time on the same band. There is a trade off when using low cross-correlations; they involve long codes. When long codes are being used; it lowers data rates that are already a challenge in acoustic communications. Doppler effects that are present in acoustic channels further reduce the correlation properties. Algorithms must be developed that are complex for demodulation and multi-user detection because CDMA gives network design issues back to the physical layer from the data link layer. Frequency hopping and direct sequence CDMA could be viable options for these modulations. Code division multiple access works best when the sound pressure levels are around the same magnitude as the systems receivers. If these magnitudes are not similar; the system could experience what is known as the near far problem. This is when nodes that are closer receive transmissions stronger than nodes that are farther away. The stronger nodes can project interference that can create issues with demodulation and detection of the weaker nodes that are farther away. The near far problem would be a greater issue with underwater sensor networks residing in deeper waters. The advantage that CDMA has over TDMA is that it can transmit data simultaneously between nodes. However, a CDMA system that experiences the far near problem is closely comparable to TDMA systems [7]. Table 1 shows a comparative performance of access technologies for underwater networks.

TABLE I. UNDERWATER CHANNEL PERFORMANCE

Parameter	CDMA	FDMA	TDMA
Scalability	✓		
Complexity			✓
Security	✓		
Synchronization			✓
Throughput	✓	✓	

IX. CONCLUSION

The development of underwater sensor networks is driven by the potential applications. These applications will advance our military capabilities to new highs, help us to discover organisms we did not know existed, study climate changes, and allow for scientific data collection to predict natural disasters before they happen. These applications will protect our country and the people from disasters and war. Discovering new organisms from the data collection taken at the bottom of the ocean could possibly be the cures we need for diseases such as cancer and AIDS. The challenges we face in building these underwater sensor networks must be studied extensively to determine the correct technological approaches to use in creating them.

Most of the protocols that are in use have been used on land dealing with radio waves. Radio waves are very different than acoustic waves in water. The way to combat these differences is to find the right combinations of equipment and protocols to make hybrid systems to use. Hybrid systems can make use of the strengths in each of the forms of technology to combat all of the design challenges and limitations. Technology trends in underwater sensors and instrumentation have led to the miniaturization and increased energy efficiency of instruments. Use of advanced manufacturing technologies, such as Micro-Electro-Mechanical Systems (MEMS) and nanotechnology, has reduced the size of instruments. Increase of platforms functionality while reducing operational costs has been achieved by integration of multiple sensors on a single platform. The research on underwater networks continues to advance, and it is encouraging that one day these underwater sensor networks will become a reality that will advance our nation to new heights over the next several years.

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