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Efficient Communication in Underwater Acoustic Networks – A survey

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Abstract

Efficient communication plays a major role with respect to oceanic applications in Underwater acoustic networks which enables the technology for applications like exploration of natural undersea resources, gathering of scientific data in collaborative monitoring missions, pollution monitoring, offshore exploration, oceanographic data collection and other surveillance applications. In this paper, we present a survey of underwater acoustic architectures and the underwater channel is being characterized. We also look into few key developments in Data Link Layer (DLL), Media Access Control (MAC) and routing protocols.

Keywords: underwater acoustic communication, media access control protocols.

INTRODUCTION

The majority of the earth's surface is covered by water. Various underwater applications like environmental monitoring, undersea explorations, disaster prevention, mine reconnaissance, *etc* have been researched [1]. Traditional monitoring systems are quite expensive and is complicated which utilizes individual and disconnected equipments to collect the data from their surrounding environments [2]. The growth of UWSNs has provided exclusive opportunities to explore the ocean in which conventional large, expensive, individual ocean monitoring equipments are being replaced by relatively small and less expensive underwater sensor nodes that can communicate with each other via acoustic signals. Many technologies for UWSNs have been researched, e.g., media access control (MAC) and secure routing protocols, localization technologies and time synchronization schemes.

CHALLENGES OF UNDERWATER ACOUSTIC COMMUNICATION

A specific set of limitations is subjected to underwater sensors which is not encountered by surface and earth based devices. Firstly, it is difficult to reach or even sometimes impossible, making maintenance operations as it is quite expensive. Accordingly, these sensors might have to optimize energy consumption [3], communicating and reporting less often and with less power than the desirable in principle [4], in order to save batteries that can never be replaced. Inclusively, the hostile conditions of water in rivers, seas and oceans, which include variable currents, animal attacks, corrosion, *etc*., may easily cause malfunctions, temporal or permanent that results in non trustable measures or breakdown of the sensors [5], that cannot be easily repaired or replaced.

Underwater acoustic communication is being influenced by path loss, noise, multi-path, doppler spread, high and variable propagation delay etc. These factors determines the temporal and spatial variability of the acoustic channel, and makes the available bandwidth of UnderWater Acoustic (UW-A) channel limited, which depends on both range and frequency. Long-range systems that operate over several tens of kilometers may have a bandwidth of only a few kHz, while a short-range system operating over several tens of meters may have more than hundred kHz bandwidth. In both cases these factors lead to low bit rates [6]. However the communication range is reduced as compared to that of the terrestrial radio channel.

Underwater acoustic communication links is being classified as very long, long, medium, short, and very short links, according to their range [7]. Table 1 shows available bandwidths for different ranges in underwater acoustic channels. On the basis of direction of the sound ray, the acoustic links can also be classified as vertical and horizontal. But the propagation characteristics of it differ consistently, with respect to time dispersion, multi-path spreads, and delay variance. Usually in oceanic literature, shallow water refers to water with depth lower than 100m, while deep water is used for deeper oceans.

Table 1: Available bandwidth for different ranges in uw-a channels

	Range[km]	**Bandwidth[kHz]**
Very Long	1000	<1
Long	10-100	2-5
Medium	1-10	~10
Short	0.1-1	20-50
Very Short	<0.1	>100

UNDERWATER ACOUSTICS ARCHITECTURE

In this section, we discuss on underwater acoustic sensor network communication architecture. These reference architectures described below are used as the basis for discussion of the challenges associated with underwater acoustic sensor networks. The underwater sensor network topology is an open research for the research community and now we discuss the following architectures:

• **Static two-dimensional UW-ASNs for ocean bottom monitoring**. These are constituted by sensor nodes that are anchored to the bottom of the ocean. Environmental monitoring, or monitoring of underwater plates in tectonics, may be few typical applications. [8].

• **Static three-dimensional UW-ASNs for ocean column monitoring**. This includes networks of sensors whose depth can be controlled by means of few techniques discussed later and may be used for surveillance applications or monitoring of ocean phenomena (ocean biogeo-chemical processes, water streams, pollution, etc).

Two-dimensional Underwater Sensor Networks

A reference architecture for two-dimensional underwater networks is shown in Fig. 1. A group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. These underwater sensor nodes are interconnected to one or more underwater sinks (uw-sinks), by means of wireless acoustic links, that relays data from the ocean bottom network to a surface station. To achieve this objective, uw-sinks are equipped with two acoustic transceivers, a vertical and a horizontal transceiver. The horizontal transceiver is used by the uw-sink to communicate with the sensor nodes in order to: i) send commands and configuration data to the sensors (uw-sink to sensors); ii) collect monitored data (sensors to uw-sink). The vertical link is used by the uwsinks to relay data to a surface station. As the ocean can be as deep as 10 km, vertical transceivers must be long range transceivers for deep water applications.

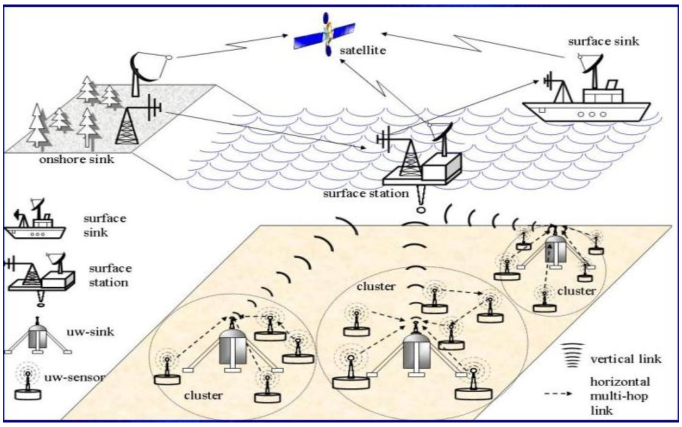

Figure 1. Architecture for 2D Underwater Sensor Networks.

The surface station has an acoustic transceiver which can handle multiple parallel communications with the deployed uw-sinks. It is also endowed with a long range RF and/or satellite transmitter to communicate with the onshore sink (os-sink) or to a surface sink (s-sink). Sensors can be connected to uw-sinks via direct links or through multi-hop paths. In the former case, each sensor directly sends the gathered data to the selected uw-sink. This is the simplest way to network sensors, but it may not be the most energy efficient, since the sink may be far from the node and the power necessary to transmit may decay with powers greater than two of the distance. Direct links reduces the network throughput because of increased acoustic interference due to high transmission power. In case of multi-hop paths, as in terrestrial sensor networks [9], the data produced by a source sensor is relayed by intermediate sensors until it reaches the uw-sink. This results in energy savings and increased network capacity but increases the complexity of the routing functionality as well. Every network device takes part in a collaborative process whose objective is to diffuse topology information so that its efficient and loop free routing decisions can be made at each intermediate node. Signaling and computation is involved in this process. Exploiting multi-hop paths and minimizing the signaling overhead, necessary to construct underwater paths at the same time is the main objective as energy and capacity are precious resources in underwater environments, in UWASN.

Three-dimensional Underwater Sensor Networks

To those phenomenons that cannot be clearly observed by means of ocean bottom sensor nodes, three dimensional underwater networks are being used i.e., to perform cooperative sampling of the 3D ocean environment. In this the sensor nodes keeps floating at different depths in order to observe a given phenomenon. Each uw-sensor node is attached to a surface buoy, by means of wires whose length can be regulated such that it adjusts the depth of each sensor node. However, there is a major drawback in this sensor network, i.e., multiple floating buoys may obstruct the ships navigating on the surface, or they can also be easily detected and deactivated by enemies in military settings, for which, a different approach can be anchored to the sensor devices to the bottom of the ocean. In this architecture, as depicted in Fig. 2, each sensor anchored at the ocean bottom are being equipped with a floating buoy which can be handled by a pump. The buoy will push the sensor towards the ocean surface. The depth of the sensor can then be regulated by adjusting the length of the wire which connects the sensor to the anchor, by means of an electronically controlled engine that resides on the sensor.

Many challenges like sensing coverage and communication coverage arise with such an architecture, that need to be solved.

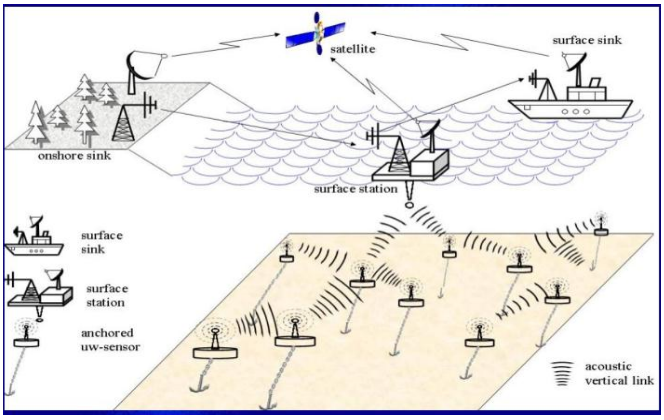

Figure 2. Architecture for 3D Underwater Sensor Network

• **Sensing coverage**. The sensors should regulate their depth collaboratively, in order to achieve full column coverage, with respect to their sensing ranges. Hence, it becomes possible to obtain the samplings of any desired depth phenomenon [44].

• **Communication coverage**. As there is no concept of uw-sink in 3D underwater networks, sensors should relay information to the surface station via multihop paths for which network devices should coordinate their depths such a way that the network topology is always connected, i.e., at least one path from every sensor to the surface station should always exist.

UNDERWATER NETWORKING

The past few decades have seen tremendous advanced growth in underwater networking. In this section, we discuss on few major developments in media access control (MAC), datalink layer (DLL) and routing protocols.

Media Access Control

Static MAC protocols are non-scalable, and in this the nodes are allocated with predetermined data channels, and are contention-free (also referred to as scheduled or deterministic protocols). Whereas in dynamic and ad-hoc schemes, the nodes typically use a shared control channel over which the data channels are requested. Centralized and distributed are the two main MAC topologies. In centralized topology which is also referred as clustered or cellular topology, there exists a master node that controls media access for all the nodes in its neighborhood. Whereas in distributed topology, there is no such controlling master node and thus all nodes asynchronously handles data transfers by itself. Dynamic MAC protocols in distributed topology are contention-based and in centralized topology, they also use polling methods with no contention.

i. Static Protocols

The traditional contention-free static MAC protocols include TDMA, FDMA and CDMA. Space division multiple access (SDMA) is rarely used. In underwater network research, its seen that FDMA is inefficient for underwater applications [43]. TDMA has been reported to be better in few aspects [44], but requires good time synchronization in nodes, whereas CDMA is favored over TDMA and FDMA [45-47]. PCLS, a loosely synchronized form of TDMA with non-overlapping timeslots, has been proposed for low capacity sensor networks [10].

ii. Dynamic Contention-based MAC in a Distributed Topology

Few of the simpler contention-based distributed protocols are half duplex ALOHA, carrier sense multiple access (CSMA) and medium access collision avoidance (MACA) using RTS/CTS handshaking [11]. Among these, MACA based protocols use RTS, CTS, DATA, ACK sequences and were shown to be effective for underwater use, compared with scheduled protocols in the Seaweb project [13]. Its observed that Adaptive modulation and Power control are the keys to maximize both channel capacity and channel efficiency, in physical and MAC layers, and RTS/CTS handshaking permits with addressing, ranging and channel estimation. MACA based protocols are found to be the best protocols for most of the underwater scenarios where time-synchronization is not available and has a very high scalability [14]. However, due to latency issues and inefficiency for small payload packets, RTS/CTS mechanisms may not perform good in some sensor networks [10]. Few protocol extensions and enhancements of MACA have been investigated, for example like WAIT command extension, to enable the protocols to perform better in underwater channel [15]. If the receiver is currently busy then a WAIT command is sent back to send the CTS later on. Due to the high propagation delay, there exits wasted bandwidth in handshaking, which is countered using a variant called PCAP, that pipelines other actions while waiting for CTS from receiver [16]. Packet trains gently improves the performance of protocols like MACA [15, 17, 18]. The analytical results for optimal packet size as a function of the acoustic link parameters like transmission rate, link distance, and error probability, along with the train or group size is of major importance [19].

In terrestrial networks, floor acquisition multiple access (FAMA), a family of protocols of which MACA is a variant, was originally proposed, which uses carrier sensing that is not present in MACA and puts restrictions on RTS/CTS time durations. To enhance the performance time-slotting is also being implemented [20]. FAMA is being suited to underwater networks because of its enhancements like slotting, otherwise FAMA in its original form would not be quite effective [14]. Distance aware-collision avoidance protocol (DACAP) is also based on MACA that adds a warning message when a RTS is overheard while waiting for a reply to its own RTS. A random back off is being used, while waiting for reply if another CTS or a warning is heard. The optimal power control for DACAP protocol is studied and this optimal power is found to minimize the connectivity. [21, 22]

iii. Dynamic Contention-based MAC in Centralized Topology

A deep-water acoustic local area network (ALAN), one of the reported network, that is deployed in Monterey Canyon, is discussed [23]. Asynchronous requests is sent by the sub-surface nodes via a shared channel (similar to MACA RTS) to send the data packets to the master node. Acknowledgement is being sent by the master node (similar to MACA CTS) via a different channel which indicates the data channel to be used. The node then starts transmitting the data immediately on that data channel. The request, ACK and data channels are of quite different frequency bands. This protocol almost is same that of MACA, except that the RTS, CTS and DATA are sent on different channels. As the transmit request is based on a shared contention channel, it is classified as a contention protocol.

iv. Dynamic Contention-free MAC in Centralized Topology

To communicate with the central node the polling-based protocol called FAMA-CF uses request for RTS (RRTS), CTS, DATA, ACK handshaking. This central node initiates RRTS to its peers, and there is one CDMA code per cluster and the spatial re-use of the codes is done. TDMA is being used within each cluster. The nodes are assumed to handle multiple CDMA codes simultaneously [24,25]. The above is classified as centralized MAC topology, since the cluster heads are given the task of TDMA slot allocation to ordinary nodes. Underwater acoustic cellular network is an extension of centralized topology. Analysis of frequency re-use between adjacent clusters and optimal cell-radius selection criteria has been carried out [26]. A related work on channel allocation and scheduling protocol for cellular networks is also made [27].

Datalink Layer Aspects

Energy conservation is a key DLL/MAC aspect. PCLS incorporates a power control and sleep-wake up scheme. Another example on energy minimization shows an ultra-low duty cycle MAC protocol focusing on energy conservation at low data rate [28]. Each node in underwater sensor system implements a time cyclic wakeup schedule in such a way that only few nodes are active at any onetime for which adaptive wakeup schedule function (AWSF), a sensor wakeup scheme is suitable [29]. The source data packets uses a novel approach to provide reliable data transfer where it virtually converts into an infinite stream which is later reorganized from the received data, provided it contains a minimum number of packets [30].

Network Layer and Routing

Fully connected peer-to-peer topologies without the need for routing could suffer from near-far power problems and thus multi-hop routing is being preferred for larger networks. Only some nodes in clustered network routing topology, have routing functionality and ordinary nodes within one-hop distance to gateways send data for routing. All the nodes are equal and perform routing to neighbors as required in fully distributed routing topology. A form of packet radio network (PRN) protocol which is a store-and-forward protocol, that matches the shallow-water acoustic channel characteristics, is implemented for shallow-water ALAN's [31,32]. The gateway node in clustered topology assuming fullduplex modems, manages route discovery through the use of probe messages to its neighbors [33]. A reverse link pointers is used in AODV protocol by assuming bi-directionally symmetric links. Location aware source routing for dynamic AUV networks that uses known TDMA frame timings to compute ranges based on propagation delay, and estimate local topology to determine routes is discussed [34,35]. A low packet error rate links is choosen by the protocol for delay tolerant applications, which maximizes the probability of correct reception, minimizing retransmissions [36]. The energy consumption is minimized for delay-sensitive applications which limits the end-to-end packet delay by estimating each hop the time to reach the sink and unacknowledged packets are not retransmitted. At the root of network coding, the idea of mixing data at intermediate nodes in a network is made [37]. Similar such schemes are considered even for underwater networks [38].

AUV NETWORKING

The wide range of increasing applications, mobility and ad-hoc requirements the networking of AUVs proposes major research efforts and challenges.

The TDMA protocol for AUVs is discussed wherein the exchanged packets contains the position information for localization and also the simulated results from a FAMA based MAC for an AUV network is obtained [39]. AUVs are sometimes equipped with multiple modems. The effective use of multiple modems optimized for different ranges in an AUV network using random access protocols is explored.

CONCLUSION

This paper has provided an overview of various Underwater Acoustic Communication challenges like path loss, noise, multi-path, doppler spread, and high and variable propagation delay. A brief discussion is also made on two dimensional and three dimensional Underwater networking architectures and a brief study is made on Underwater networking, where we study few key developments in Data Link layer (DLL), Media Access Control (MAC) and routing protocols.

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