Challenges: Building Scalable and Distributed Underwater Wireless Sensor Networks (UWSNs) for Aquatic Applications

Jun-Hong Cui, Jiejun Kong, Mario Gerla, Shengli Zhou

jcui@cse.uconn.edu, jkong, gerla@cs.ucla.edu, shengli@engr.uconn.edu

UCONN CSE Technical Report: UbiNet-TR05-02

Last Update: September 2005

Abstract

Large-scale Underwater Wireless Sensor Network (UWSN) is a novel networking paradigm to explore the uninhabited and complex oceans. However, the characteristics of UWSNs, such as huge propagation delay, floating node mobility, and limited acoustic link capacity, are significantly different from ground-based wireless sensor networks and existing small scale Underwater Acoustic Networks (UANs). The novel networking paradigm poses inter-disciplinary challenges that will require new technological solutions. In particular, in this technical report we adopt a top-down approach to explore the research challenges in UWSN design. Along the layered protocol stack, we roughly go down from the top application layer to the bottom physical layer. At each layer, a set of new design intricacies are studied. The conclusion is that building scalable and distributed UWSNs is a challenge that must be answered by inter-disciplinary efforts of acoustic communications, signal processing and mobile acoustic network protocol design.

I. INTRODUCTION

The largely unexplored vastness of the ocean, covering about two-thirds of the surface of Earth, has fascinated humans for as long as we have records. Its currents, chemical composition, and ecosystems are all highly variable as a function of space and time. Recently, there has been a growing interest in monitoring the marine environment for scientific exploration, commercial exploitation and coastline protection. The ideal vehicle for this type of extensive monitoring is a networked underwater wireless sensor distributed system, referred to as **Underwater Wireless Sensor Network (UWSN)**. A distributed and scalable UWSN provides a promising solution for efficiently exploring and observing the ocean which operates under the following constraints:

1) Unmanned underwater exploration: Underwater condition is not suitable for human exploration. High water pressure, unpredictable underwater activities, and vast size of water area are major reasons for un-manned exploration.

2) Localized and precise knowledge acquisition: Localized exploration is more precise and useful than remote exploration because underwater environmental conditions are typically localized at each venue and variable in time. Using long range SONAR or other remote sensing technology may not acquire adequate knowledge about physical events happening in the volatile underwater environment.

3) Tetherless underwater networking: The Internet is expanding to outer space and underwater. Undersea explorer

Dr. Robert Ballard has used Internet to host live, interactive presentations with students and aquarium visitors from the wreck of the Titanic, which he found in 1985. However, while the current tethered technology allows constrained communication between an underwater venue and the ground infrastructure, it incurs significant cost of deployment, maintenance, and device recovery to cope with volatile undersea conditions.

4) Large scale underwater monitoring: Traditional underwater exploration relies on either a single high-cost underwater device or a small-scale underwater network. Neither existing technology is suitable to applications covering a large area. Enabling a scalable underwater sensor network technology is essential for exploring a huge underwater space.

By deploying distributed and scalable wireless sensor networks in 3-dimensional underwater space, each underwater sensor can monitor and detect environmental events locally. Such can be accomplished with fixed position sensors. However the oceanic system is also dynamic and processes occur within the water mass as it advects and disperses within the environment. Therefore a mobile and dynamic observation system is optimal. The self-organizing network of mobile sensors provides better supports in sensing, monitoring, surveillance, scheduling, underwater control, and fault tolerance. Hence, we are equipped with a better sensing and surveillance technology to acquire precise knowledge about unexplored underwater venues.

Underwater Wireless Sensor Network (UWSN) is a novel technique. *It is significantly different from any ground-based sensor network*: First, RF radio does not work well in underwater environment. Instead, acoustic modem should be used. Unlike wireless links among ground-based sensors, underwater acoustic channels feature large-latency and low-bandwidth; Second, most sensor nodes in ground-based sensor networks are typically static. In contrast, majority of underwater sensor nodes (except some fixed nodes equipped on surface-level buoys) are mobile due to water currents and the sensors shift position relative to one another as a result of dispersion and shear processes; Third, the system lifetime of an underwater sensor network may vary from several minutes to several years due to various applications ranging from a short-term naval investigation or an anti-submarine event to long-term underwater monitoring. To develop an effective underwater sensor network, communication protocols used in ground-based sensor networks may not be suitable in underwater sensor networks. Instead, all the above special characteristics: low bandwidth, large latency, mobility, and wide range of system requirements should be considered.

Furthermore, *UWSN is different from existing small-scale Underwater Acoustic Network (UAN)* [43] [39] [53]. A UWSN is a scalable sensor network, which relies on localized sensing and coordinated networking amongst large numbers (potentially hundreds to thousands) of low-cost and densely-deployed sensors. For example, after sensors are dispersed in an initial deployment they will begin to disperse with the advective currents and dispersion that characterize the oceanic environment. And since dispersion is scalable, the more the sensors disperse, the faster they will continue to disperse. In addition, because of shear, currents at depth will be different than currents at the surface and sensors will spread in unknown ways. Thus in order to remain viable, the sensor networks need to be able to reconfigure a communication path via a continuous route that is independent of the last path by which communication was made. In contrast, an existing UAN is a small-scale and sparsely-deployed network (with usually less than tens of nodes) relying on data collecting strategies like remote telemetry or assuming point-to-point communication. Compared to local sensing, remote telemetry is very costly if designed for high precision. The network protocols used in UANs with point-to-point communication are usually borrowed from ground-based wireless ad hoc networks. These techniques can not be directly applied to large-scale sensor networks [25]. Moreover, in UAN systems, since sensors are usually fixed (either anchored in the sea floor or attached to surface buoys with GPS), localization schemes (i.e., methods to determine the locations of sensors) are not needed. However, in UWSNs, localization is a must for mobile sensors nodes. Thus, techniques used in UANs are incomplete for the needs of UWSNs.

In a nutshell, existing ground-based sensor network or UAN techniques cannot meet a wide variety of aquatic application demands to implement a localized, precise, and large-scale sensing technology in aquatic environments. Due to the complexity of the aquatic environments and the sophistication of the user scenarios, designing a distributed and scalable UWSN is a very challenging task. This requires new research at almost every level of the protocol suite.

In this technical report, next we will first review the characteristics of acoustic communications and some related work on ground-based wireless sensor networks and underwater acoustic networks, and identify the distinct features of UWSNs and pinpoint the crucial principle of the network architecture design. Based on the unique features of UWSNs and the wide range system requirements of various aquatic applications, we then propose two network architectures: one for *short-term time-critical aquatic exploration applications*, and the other for *long-term non-time-critical aquatic monitoring applications*. To explore the design challenges across different types of network architectures, we adopt a top-down approach, by roughly going down from the top application layer to the bottom physical layer according to the well-known network protocol stack. At the end, we conclude that building scalable and distributed UWSN is a challenge that must be answered by inter-disciplinary efforts of acoustic communications, signal processing and mobile acoustic network protocol design.

II. BACKGROUND AND RELATED WORK

A. *Underwater Acoustic Channels*

Underwater acoustic channels are temporally and spatially variable due to the nature of the transmission medium and physical properties of the environments. The signal propagation speed in underwater acoustic channel is about 1.5×10^3 m/sec, which is five orders of magnitude lower than the radio propagation speed (3×10^8 m/sec). The available bandwidth of underwater acoustic channels is limited and dramatically depends on both transmission range and frequency. The acoustic band under water is limited due to absorption, most acoustic systems operate below 30kHz. Table I briefly overviews the relation between bit-rate and transmission range. From the reports of empirical measurements, the range-rate product is limited in the range of $[10 \sim 70]$ km*kbps. The bandwidth of underwater acoustic channels operating over several kilometers is about several tens of kbps, while short-range systems over several tens of meters can reach hundreds of kbps.

In addition to these inherent properties, underwater acoustic communication channels are affected by many factors

TABLE I

REPORTED RELATION BETWEEN DATA RATE AND TRANSMISSION RANGE

Reported in	Modulation Method	Bandwidth (kHz)	Bandwidth Carrier (kHz)	Data Rate (kbps)	Range (km)	Range-Rate Product (km*kbps)
[27]	16QAM	125	1000 ± 62.5	500	0.06	30
[45]	4,8PSK	10	25 ± 5	$20 - 30$	3.5	70
[11], [12]	BPSK	0.2	7 ± 0.1	0.2	50	10

such as path loss, noise, multi-path, and Doppler spread. All these factors cause high bit-error and delay variance. Acoustic links are also roughly classified as vertical and horizontal, according to the direction of the sound ray. Their propagation characteristics differ consistently, especially with respect to time dispersion, multi-path spreads, and delay variance. The difference is caused by the chemical-physical properties of the water medium such as temperature, salinity and density, and by their spatio-temporal variations. These variations, together with the wave guide nature of the channel, cause the acoustic channel to be temporally and spatially variable. In particular, the horizontal channel is by far more rapidly varying than the vertical channel, in both deep and shallow water.

In short, underwater acoustic channels are featured with large propagation delay, large delay variance, limited available bandwidth and high error probability. Furthermore, the bandwidth of underwater acoustic channels is determined by both the communication range and frequency of acoustic signals. The bigger the communication range, the lower the bandwidth of underwater acoustic channels.

B. Distinctions Between UWSNs and Ground-Based Sensor Networks

A UWSN is significantly different from any ground-based sensor network in terms of the following aspects:

Communication Method Electromagnetic waves cannot propagate over a long distance in an underwater environment. Therefore, underwater sensor networks have to rely on other physical means, such as acoustic sounds, to transmit signals. Unlike wireless links among ground-based sensors, each underwater wireless link features large-latency and low-bandwidth. Due to such distinct network dynamics, communication protocols used in ground-based sensor networks may not be suitable in underwater sensor networks. Especially, low-bandwidth and large-latency usually result in long end-to-end delay, which brings big challenges in reliable data transfer and traffic congestion control. The large latency also significantly affects multiple access protocols. Traditional random access approaches in RF wireless networks might not work efficiently in underwater scenarios.

Mobility Most sensor nodes in ground-based sensor networks are typically static, though it is possible to implement interactions between these static sensor nodes and a limit amount of mobile nodes (e.g., mobile data collecting entities like “mules” which may or may not be sensor nodes). In contrast, majority of underwater sensor nodes, except some fixed nodes equipped on surface-level buoys, are with low or medium mobility due to water current and other underwater activities. From empirical observations, underwater objects may move at the speed of 2-3 knots (or 3-6 kilometers per hour) in a typical underwater condition. Therefore, if a network protocol proposed for ground-based sensor networks does not consider mobility for majority of sensor nodes, it would likely fail when directly cloned for aquatic applications.

Wide Range of System Requirements The system lifetime of an underwater sensor network may vary from several minutes to several years. (1) In a naval investigation or an anti-submarine event, a deployed UWSN is needed for merely several minutes. (2) In underwater monitoring, long-term underwater sensor nodes can be powered by micro hydroelectric generators. Some state-of-art hydroelectric generators weigh about 30 lbs and generate power up to 1000 watts. Thus the system lifetime could last for years. Such heterogeneous system requirements are challenging underwater sensor network designs.

Although there have been extensive research in ground-based sensor networks, due to the unique features of UWSNs, new research at almost every level of the protocol suite is required.

C. Current Underwater Network Systems and Their Limitations

A scalable Underwater Wireless Sensor Network (UWSN) is a major step forward with respect to existing small-scale Underwater Acoustic Networks (UANs) [1] [2] [3] [43] [39] [53]. The major differences between UANs and UWSNs lie in the following dimensions:

Scalability: A UWSN is a scalable sensor network, which relies on localized sensing and coordinated networking among large numbers of low-cost sensors. In contrast, an existing UAN is a small-scale network relying on data collecting strategies like remote telemetry or assuming that communication is point- to-point. In remote telemetry, data is remotely collected by long-range signals. Compared to local sensing, the precision of this method is strongly affected by environmental conditions, and the cost of this method can be unreasonably high to meet the demands of high-precision applications. In UANs, where point-to-point communication is assumed, sensor nodes are usually sparsely distributed (in several kilometers), thus no multi-access technique is needed, while in UWSNs, sensor nodes are densely deployed in order to achieve better spacial coverage, thus a well-designed multi-access protocol is a must to avoid/reduce collision and improve the system throughput.

Self-organization: In UANs, nodes are usually fixed (thus there are no multiple mobile sensors dispersing) while a UWSN is a self-organizing network. Underwater sensor nodes may be redistributed and moved by the aqueous processes of advection and dispersion. After transport by the currents and dispersion, the sensors must re-organize as a network in order to maintain communication. Thus, sensors should automatically adjust their buoyancy, moving up and down based on measured data density. In this way, sensors are mobile in order to track changes in the water mass rather than make observations at a fixed point. The protocols used in UANs (which are usually borrowed from ground-based wireless ad hoc networks) cannot be directly employed by UWSNs to handle self-organized sensors with slow data rates and high dispersion rates.

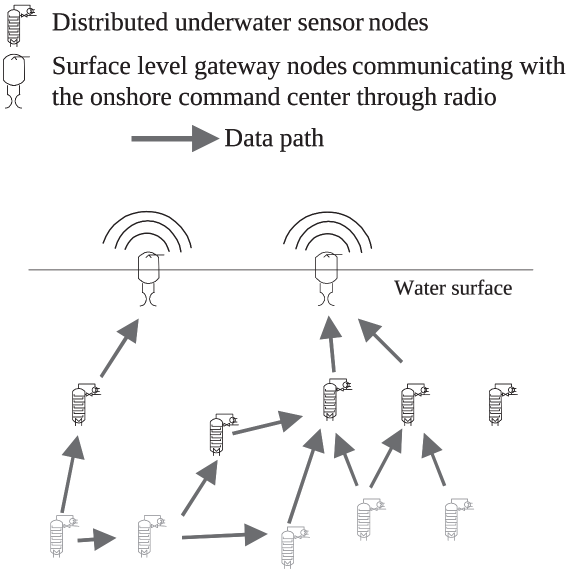

Fig. 1. An illustration of the UWSN architecture for long-term non-time-critical aquatic monitoring applications

Localization: In UANs, sensor localization is not desired since nodes are usually fixed, either anchored in the sea floor or attached to buoys with GPS systems. However, in UWSNs, localization is required because majority of the sensors are mobile with the current. Determining the locations of mobile sensors in aquatic environments is very challenging. On the one hand, we need to face the limited communication capabilities of acoustic channels. On the other hand, we have to take care of the localization accuracy due to the node mobility.

In summary, the techniques used in an existing UAN cannot directly applied to a UWSN.

III. TWO NETWORKING ARCHITECTURES FOR UWSNS

In general, depending on the permanent vs on-demand placement of the sensors, the time constraints imposed by the applications and the volume of data being retrieved, we could classify the aquatic application scenarios into two broad categories: long-term non-time-critical aquatic monitoring and short-term time-critical aquatic exploration. Applications fall in the first category include oceanography, marine biology, deep-sea archaeology, seismic predictions, pollution detection, and oil/gas field monitoring, to name a few. The examples for the second category are underwater natural resource discovery, hurricane disaster recovery, anti-submarine military mission, and loss treasure discovery, etc. In the following, we present a UWSN architecture for each type of aquatic applications, and pinpoint the key design issues in each of the UWSN architecture.

A. UWSN for Long-Term Non-Time-Critical Aquatic Monitoring

Fig. 1 illustrates the UWSN architecture for long-term non-time-critical aquatic monitoring applications. In this type of network, sensor nodes are densely deployed to cover big and spacial continuous monitoring areas. Data are collected by local sensors, related by intermediate sensors, and finally reach the surface nodes (equipped with both acoustic and RF (Radio Frequency) modems), which can transmit data to the on-shore command center by radio.

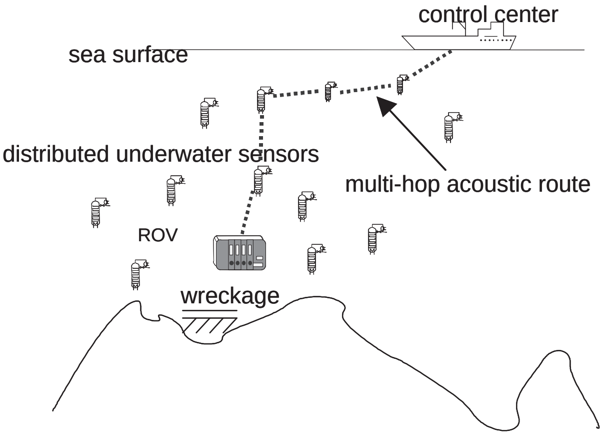

Fig. 2. An illustration of the UWSN architecture for short-term time-critical aquatic exploration applications

Since this type of network is designed for long-term monitoring task, then energy saving is a central issue to consider in the protocol design. Among the four types of sensor activities (sensing, transmitting, receiving, and computing), transmitting is the most expensive in terms of energy consumption. Efficient techniques for multi-access and data forwarding play a significant role in reducing energy consumption. Moreover, depending the data sampling frequency, we may need mechanisms to dynamically control the mode of sensors (switching between sleeping mode, wake-up mode, and working mode). In this way, we may save more energy. Further, when sensors are running out of battery, they should be able to pop up to the water surface for recharge, for which a simple air-bladder-like device would suffice.

Clearly, in the UWSNs for long-term aquatic monitoring, localization is a must-to-do task to locate mobile sensors, since usually only location-aware data is useful in aquatic monitoring. In addition, the sensor location information can be utilized to assist data forwarding since geo-routing proves to be more efficient than pure flooding. Furthermore, location can help to determine if the sensors float to the boundary of the interested area. If this happens, the sensors should have some mechanisms to relocate (self-propelled) or pop up to the water surface for manually redeployment.

Lastly, reliable, resilient, and secure data transfer is required to ensure a robust observing system in the presented UWSN architecture.

B. UWSN for Short-Term Time-Critical Aquatic Exploration

In Fig. 2, we show a civilian scenario of the UWSN architecture for short-term time-critical aquatic exploration applications. Assume a ship wreckage & accident investigation team want to identify the target venue. Existing approaches usually employ tethered wire/cable to a remotely operated vehicles (ROV). When the cable is damaged the ROV is out-of-control or not recoverable. In contrast, by deploying a *high data rate* underwater wireless sensor network, as shown in Fig. 2, the investigation team can control the ROV remotely. The self re-configurable underwater sensor network tolerates more faults than the existing tethered solution. After investigation, the underwater sensors can be recovered by issuing a command to trigger air-bladder devices.

In military context, submarine detection is an example of the target short-term time-critical aquatic exploration applications. In the face of state-of-art stealthy technologies, the acoustic signature of a modern submarine can only be identified within a very short range. Compared to remote sensing technology that has limited accuracy and robustness, the self-configured sensor mesh can identify the enemy's submarine with very high probability since every individual sensor is capable of submarine detection, and moreover, the detection can be reinforced by multiple observations. We can still use Fig. 2 to depict this application scenario, with the ROV replaced with enemy's stealthy submarine. The self-reconfigurable wireless sensor network detects the enemy's submarine and notifies the control center via multi-hop acoustic routes.

This type of aquatic applications demand rates ranging from very small (e.g., send an alarm that a submarine was detected) to relatively high (e.g., send pictures, or even live video of the submarine). As limited by acoustic physics and coding technology, high data rate networking can only be realized in high-frequency acoustic band in underwater communication. It was demonstrated by empirical implementations [27] that the link bandwidth can reach up to 0.5Mbps at the distance of 60 meters. Such high data rate is suitable to deliver even multimedia data.

Compared with the first type of UWSN for long-term non-time-critical aquatic monitoring, the UWSN for shot-term time-critical aquatic exploration presents the following differences in protocol design.

- Real-time data transfer is more concerned.
- Energy saving becomes a secondary issue.
- Localization is not a must thing to do.

However, reliable, resilient, and secure data transfer is a always-desired advanced feature for both types of UWSNs.

C. Discussions

We have just described two UWSN architectures, both of which involve mobile dynamic sensor nodes. In our vision, this is ideal in the long run for various aquatic applications. However, due to the harsh underwater conditions, in the short term, for some applications we may want to seek for some intermediate solutions. One example is seismic monitoring for oil extraction from underwater fields [21], for which the monitoring task is mainly conducted on the sea floor. A natural network architecture for this application is to deploy fixed sensors, which are anchored to the sea floor. Some intermediate nodes attached with surface buoys can be used for data forwarding. The recent paper [6] also presents a similar network architecture. Clearly, this type of architecture does not have sensor node mobility, which actually incurs many additional challenges in our proposed network architectures. However, we argue that there are still many common design issues across this "static" UWSN architecture and our "mobile and dynamic" UWSN architectures, especially on the lower layers of the protocol stack, such as efficient acoustic communications, efficient multiple access, and distributed localization and time synchronization, for which we will present our study in the next section.

IV. CHALLENGES IN COMMUNICATIONS, SIGNAL PROCESSING AND MOBILE NETWORK DESIGN

In this section we identify the design challenges along the network protocol stack in a top-down manner. We will see that at each layer, there are many critical problems awaiting solutions.

A. *Security, Resilience and Robustness*

One area which will definitely require revisiting (with respect to prior work in ground-based ad hoc and sensor networks) is vulnerability to security threats. This is actually a cross-layer issue that affects the entire protocol stack. To realize a scalable ad hoc network, nodes must be low-cost and economically viable. They are limited in energy, computation, and communication capabilities. This makes many existing security mechanisms inadequate, and hence inspires new security research, such as efficient key management [16] [15], authentication [37], data privacy and anonymity [34] [14], that avoid expensive crypto-operations. Nevertheless, a self-organizing ad hoc network needs more protections than cryptography. Many security attacks continue to threaten ad hoc networks even when an ideal cryptosystem is efficiently protecting the network. A critical security issue is to defend against denial-of-service attack, which could be in the form of (1) depleting node's on-device resource (especially draining battery by incurring extra computation and communication) and (2) disrupting network collaboration (e.g., routing, data aggregation, localization, clock synchronization). Such attacks can disrupt or even disable ad hoc networks and sensor networks independent of cryptographic protections.

In [29], we study security attacks threatening collaborative underwater network services. We show that, no matter what kind of protocol stack we are building, a UWSN can be disabled by low-cost underwater denial-of-service attacks due to the unique characteristics of underwater acoustic channels. In particular, wormhole attack [24] and its variants impose great threat to underwater acoustic communications. Many countermeasures that have been proposed to stop wormhole attack in radio networks are ineffectual in UWSNs. In [29], we show that low-cost wormhole links of *any* length effectively disrupt communication services in UWSNs. The adversary can implement wormholes longer than or shorter than the one-hop transmission range. Because many existing wormhole countermeasures proposed for radio networks [23] [48] only ensure that a transmitter and its receiver are physically one-hop neighbors, they *cannot* be used to counter underwater wormholes shorter than one-hop distance. Moreover, no signal, including those from the adversary, can propagate faster than the radio signals in ground ad hoc networks. Many existing wormhole countermeasures proposed for radio networks [24] [48] [49] exploit this fact to bound the distance between a sender and its receiver. Nevertheless, in the underwater acoustic channel such distance-bounding schemes [9] are ineffective against wormholes.

Another kind of problem that may arise in UWSNs is intermittent partitioning due to water turbulence, currents, and ships etc. In fact, there may be situations where no connected path exists at any given time between source and destination. This intermittent partitioning situation may be detected through routing and by traffic observations. A new network paradigm that deals with such disruptions was recently developed, namely Disruption Tolerant Networking (DTN) [18]. DTN includes the use of intermediate store and forward proxies. If the data sink (i.e., the command center in wireless sensor networks) suspects the presence of such conditions, it can then take advantage of some of the DTN techniques to reach the data sources.

B. Reliable and/or Real-Time Data Transfer

Reliable data transfer is of critical importance. There are typically two approaches for reliable data transfer: end-to-end or hop-by-hop. The most common solution at the transport layer is TCP (Transmission Control Protocol), which is an end-to-end approach. We expect TCP performance to be problematic because of the high error rates incurred on the links, which was already encountered in wireless radio networks. Under the water, however, we have an additional problem: propagation time is much larger than transmission time, setting the stage for the well known large $bandwidth \times delay$ product problem. Consider a path with 20 nodes spaced by 50m with rate of 500Kbps and packet size = 1000 bits. The optimal TCP window is therefore 2000 packets. Managing such unusually large windows with severe link error rates is a major challenge since TCP would time out and would never be able to maintain the maximum rate. There are a number of techniques that can be used to render TCP performance more efficient, for instance, the use of TCP variants (like TCP Westwood [31]) that are robust to errors. However, what is the performance of these TCP variants in UWSNs is yet to be investigated.

Another type of approach for reliable data transfer is hop-by-hop. The hop-to-hop approach is favored in wireless and error-prone networks, and is believe to be more suitable for sensor networks. Wan et al. designed PSFQ (Pump Slowly and Fetch Quickly) [50], which employs the hop-by-hop approach. In this protocol, a sender sends data packet to its immediate neighbors at very slow rate. When the receiver detects some packet losses, it has to fetch the lost packets quickly. The rate of fetching lost packet is 5 times as fast as the rate of sending data. Hop-by-hop, data packets are finally delivered to the data sink reliably. In PSPQ, ARQ (Automatic Repeat Request) is used hop-by-hop. However, due to the long propagation delay of acoustic signals, ARQ causes low utilization of acoustic channels in UWSNs. One possible solution to solve the problem is to investigate erasure coding schemes, which, though introducing redundant overhead, can avoid re-transmission delay. The challenge is to design a tailored efficient coding scheme for UWSNs.

As mentioned earlier, real-time data transfer is desired for short-term time-critical aquatic exploration applications. To provide time-constrained services is yet another tough research problem in the network community, even for the Internet. In the Internet, UDP (User Datagram Protocol) is usually favored over TCP for real-time service since UDP does not throttle data flows and allows data to transfer as fast as possible. However, in order to provide reliable data transfer as well, UDP like approach obviously does not work. In ground-based ad hoc networks and sensor networks, path redundancy is usually exploited to improve reliability. In UWSNs, due to the high error probability of acoustic channels, efficient erasure coding schemes could be utilized to help achieve high reliability and at the same time reduce data transfer time by suppressing retransmission.

C. Traffic Congestion Control

Congestion control is an important while tough issue to study in many types of networks. In UWSNs, high acoustic propagation delay makes congestion control even more difficult. In ground-based sensor networks, congestion detection and avoidance are first probed in ESRT (Event to Sink Reliable Transport) [41]. ESRT is a transportation protocol for homogeneous sensor networks where each node has the same sending rate. If some nodes in the network detect congestion, they mark the related packets. Upon receiving such marked packets, the sink can conclude that there exists congestion in the network and broadcasts command to regulate the sending rate of the sources. Each source reduces its report rate accordingly. The congestion control problem is more thoroughly investigated in CODA (Congestion Detection and Avoidance) [51]. In CODA, there are two mechanisms for congestion control and avoidance: open-loop hop-by-hop backpressure and closed-loop multi-source regulation. In the open-loop hop-by-hop backpressure mode, a node broadcasts a backpressure message as soon as it detects congestion. The backpressure message will be propagated upstream toward source nodes. In a densely deployed network, the backpressure message will be most likely to reach the source directly. In the closed-loop multi-source regulation, the source uses the ACKs from the sink to self-clock.

For UWSNs, we expect a combination of open and closed loop may work best, providing a good compromise between fast reaction (with open) and efficient steady state regulation (with closed). One aspect deserves further investigation is the distinction between loss due to congestion and loss due to external interference. Most schemes assume all loss is congestion related. The higher the loss, the lower becomes the source rate. This will cause problems in underwater system where random errors/loss may be prevalent. From received packet inter-arrival statistics and from other local measurement, the data sink may be able to infer random loss versus congestion and maintain the rate (and possibly strengthen the channel coding) if loss is not congestion related.

D. Efficient Multi-Hop Acoustic Routing

Like in ground-based sensor networks, saving energy is a major concern in UWSNs (especially for the long-term aquatic monitoring applications). Another challenge for data forwarding in UWSNs is to handle node mobility. This requirement makes most existing energy-efficient data forwarding protocols unsuitable for UWSNs. There are many routing protocols proposed for ground-based sensor networks, such as Directed Diffusion [25], TTDD (Two-Tier Data Dissemination) [54], GRAdient [55] and Rumor routing [8], and SPIN (Sensor Protocol Information via Negotiation) [22]. These protocols are mainly designed for stationary networks. They usually employ query flooding as a powerful method to discover data delivery paths. In UWSNs, however, most sensor nodes are mobile, and the "network topology" changes very rapidly even with small displacements due to strong multipath. Thus, the existing routing algorithms using query flooding designed for ground-based sensor networks are no longer feasible in UWSNs because the state of the path changes rapidly and significantly.

The multi-hop routing protocols in ground-based mobile ad hoc networks fall into two categories: proactive routing and reactive routing (aka., on demand routing) [10]. In proactive ad hoc routing protocols like OLSR [4], TBRPF [33] and DSDV [35], mobile nodes constantly exchange routing messages which typically include connection status to other nodes (e.g., link state or distance vector), so that every node maintains sufficient and fresh network topological information to allow them to find any intended recipients at any time. On the other hand, on demand routing has become a major trend in mobile networks. AODV [36] and DSR [26] are common examples. Unlike their proactive counterparts, on-demand routing operation is triggered by the communication demand at sources. Typically, an on-demand routing protocol has two components: *route discovery* and *route maintenance*. In route discovery phase, the source seeks to establish a route towards the destination by *flooding* a route request (RREQ) message, then waits for the route reply (RREP) which establishes the on-demand route. In the route maintenance phase, nodes on the route monitor the status of the forwarding path, and report to the source about route errors.

Nevertheless, flooding is no longer a robust-and-efficient tool in large scale underwater networking. Moreover, the cost of proactive neighbor detection could be more expensive than flooding again because of the large scale of UWSNs. With no proactive neighbor detection and with less flooding, it is a big challenge to furnish multi-hop ad hoc packet delivery service in UWSNs with node mobility requirement. One possible direction is to utilize location information to do geo-routing. But how to make geo-routing energy-efficient in UWSNs is yet to be answered.

E. Distributed Localization and Time Synchronization

In aquatic applications, it is critical to let every underwater node know its current position and the synchronized time with respect to other coordinating nodes. Nevertheless, the high-frequency radio wave used by Global Positioning System (GPS) is quickly absorbed by water, hence cannot propagate deeply under the water surface. So far, to our best knowledge, a scalable and low-cost positioning and time-synchronization system like GPS for ground sensor nodes is not yet available to underwater sensor nodes.

It is expected that underwater networks must rely on *distributed GPS-free localization and time synchronization schemes* to let the sensor nodes know their positions and the network clock value. In other words, before the network can use geo-routing schemes, it needs a multi-hop packet delivery service, which must be GPS-free. In a nutshell, in UWSNs, network-wise localization and time-sync services strongly rely on multi-hop ad hoc packet delivery service. This is significantly different from ground-based mobile ad hoc networks and wireless sensor networks where GPS services are typically available, for example, directly from GPS interfaces in outdoor cases and about 2 or 3 hops away in indoor cases.

The key problem in a network with node mobility is the range and direction measurement process itself. Unfortunately, we are left with only a few choices. The common GPS-free approach used in many ground-based sensor networks of measuring the Time-Difference-of-Arrival (TDoA) between an RF and an acoustic/ultrasound signal (e.g., the AhLoS project [42] and the Cricket project [38]) is no longer feasible as the commonly available RF signal fails under water. Receiver-signal-strength-index (RSSI) [7] is vulnerable to acoustic interferences like near-shore tide noise, near-surface ship noise, multi-path, and Doppler frequency spread. Angle-of-Arrival (AoA) systems [32] require directional transmission/reception devices, which would incur non-trivial extra cost.

Possible approaches may include acoustic-only Time-of-Arrival (ToA) approaches (e.g. measuring round-trip time by actively bouncing the acoustic signal only) as well as deploying many surface-level radio anchor points (via GPS for instant position and time-sync info). Moreover, the underwater environment with motion of water, and variation in temperature and pressure also affects the speed of acoustic signal. Sophisticated signal processing will be needed to compensate for these sources of errors due to the water medium itself.

F. Efficient Multiple Access

The peculiarities of the underwater acoustic channel, especially limited bandwidth and high transmission delays, also pose unique challenges for media access control (MAC) that enables multiple devices to share a common wireless medium in an efficient and fair way [39] [5]. MAC protocols can be roughly divided into two main categories: i) scheduled protocols that avoid collision among transmission nodes, and ii) contention based protocols where nodes compete for a shared channel, resulting in probabilistic coordination. Scheduled protocols include time-division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA), where users are separated in time, frequency, or code domains. These protocols have been widely used in modern cellular communication systems [40]. Contention based protocols include random access (ALOHA, slotted ALOHA), carrier sense access (CSMA), and collision avoidance with handshaking access (MACA, MACAW) [56] [5], which is the basis of several widely-used standards including IEEE 802.11.

It has been observed that contention based protocols that rely on carrier sensing and handshaking are not appropriate in underwater communications [39] [5]. One may want to investigate if ALOHA/slotted ALOHA works under the water since satellite networks, which also share the feature of long propagation delay, employ these random access approaches. On the other hand, FDMA is not suitable due to the narrow bandwidth of underwater acoustic channel and TDMA is not efficient also due to the excessive propagation delay [39] [5]. As a result, CDMA has been highlighted as a promising multiple access technique for underwater acoustic networks [39] [5]. If multiple antenna elements are deployed at certain relay or access points, then spatial division multiple access (SDMA) is a viable choice [13]. Like in CDMA, users can transmit simultaneously over the entire frequency band. With different spatial signature sequences, users are separated at the receiver through interference cancellation techniques. SDMA and CDMA can be further combined, where each user is assigned a signature matrix that spreads over both space and time, extending the concept of temporal or spatial spreading. Since multiple colliding users may be successfully recovered via advanced receiver processing, it is appropriate to adopt the advanced multi-packet reception (MPR) model rather than the simple collision model for performance analysis and optimization [47].

G. Acoustic Physical Layer

Compared with the counterpart on radio channels, communications over underwater acoustic channels are severely rate-limited and performance-limited. That is due to the inherent bandwidth limitation of acoustic links, the large delay spread and the high time-variability due to slow sound propagation in underwater environment. As a result, unlike the rapid growth of wireless networks over radio channels, in the last two decades we have only witnessed two fundamental advances in underwater acoustic communications. One is the introduction of digital communication techniques (non-coherent frequency shift keying (FSK)) in early 1980's, and the other is the application of coherent modulations, including phase shift keying (PSK) and quadrature amplitude modulation (QAM) in early 1990's [28], [44]. Following the deployment of coherent systems, performance improvement has been moderate, and mostly only due to receiver enhancement [28]. Substantial innovations are needed at the physical layer to robustify the system performance and offer significantly higher data rate for underwater communication networks.

Due to the large delay spread and high time variability, underwater acoustic channel is one typical example of the so called doubly-selective (both time- and frequency- selective) channels. Hence, underwater communications face the same signal-design challenges as future-generation wireless systems targeting at high date rate and high mobility simultaneously. Note that current wireless systems can effectively deal with time-selectivity (e.g., in narrowband cellular systems where high mobility is allowed), or, frequency-selectivity (e.g., in wireless LAN (Local Access Network) where high rate is available but only "portability" rather than "mobility" is supported), but only in a separate manner. Existing approaches for underwater communications model the channel as frequency selective for equalization, while dealing with the time variation via a channel tracking unit. This does not fully exploit the potential of doubly selective channels, which can provide a maximum diversity order as the product of the diversity orders in the frequency dimension and in the Doppler dimension (due to time variations) [30]. To jointly exploit the frequency- and Doppler- diversities, *block* based transmission schemes, either single-carrier or multi-carrier (e.g., orthogonal frequency division multiplexing), are required [30], [52]. Block transmission schemes are likely to offer much improved performance over existing *symbol* based counterparts.

Subject to the inherent limited bandwidth of acoustic links, high rate communication is very challenging over underwater acoustic channels. Multi-input multi-output (MIMO) techniques, enabled by the deployment of multiple antenna elements at both the transmitter and the receiver, offer a big promise fundamentally. With N antennas at the transmitter and M antennas at the receiver, the capacity of the MIMO wireless link increases linearly as min(N,M), without any penalty on the transmission bandwidth and power [19], [46]. The success of MIMO techniques has been demonstrated by the significant rate improvement in enhanced cellular and wireless local area networks [20]. Due to the small wavelength (e.g., wavelength=7.5 cm for a 20 kHz carrier), it is plausible to place uncorrelated antenna arrays (say $2 \sim 4$ elements) in underwater sensors. Some gateway or relay sensors could be equipped with more elements. On the one hand, MIMO techniques improve considerable the transmission rate. Early trials of spatial modulation in underwater environments are reported in [17], where a significant capacity increase is shown achievable. On the other hand, antenna arrays at the receiver side can be used for performance enhancement via interference cancellation.

V. SUMMARY

In this technical report, we call for the attention to build scalable and distributed UWSNs for aquatic applications. We identify the unique characteristics of UWSNs, and present two network architectures for different types of aquatic applications, identifying their key requirements in protocol design. We further analyze the design challenges of implementing the needed underwater networks. Following a top-down approach, we discuss the design challenges of each layer in the network protocol stack. Our study shows that designing UWSNs is an inter-disciplinary challenge requiring integration of acoustic communications, signal processing and mobile network design.

REFERENCES

[1] The ARGOS Data Collection System. *http://noaasis.noaa.gov/ARGOS/.*

[2] The RAFOS Float Group. *http://www.po.gso.uri.edu/rafos/.*

[3] The SeaWeb Project. *http://www.seaweb.org/.*

[4] C. Adjih, T. Clausen, P. Jacquet, A. Laouiti, P. Minet, P. Muhlethaler, A. Qayyum, and L. Viennot. Optimized Link State Routing Protocol. Internet Draft.

[5] I. F. Akyildiz, D. Pompili, and T. Melodia. Challenges for Efficient Communication in Underwater Acoustic Sensor Networks. *ACM SIGBED Review*, Vol. 1(1), July 2004.

[6] I. F. Akyildiz, D. Pompili, and T. Melodia. Underwater Acoustic Sensor Networks: Research Challenges. *Ad Hoc Networks Jounal (Elseviier)*, March 2005.

[7] P. Bahl and V. N. Padmanabhan. RADAR: An In-Building RF-Based User Location and Tracking System. In *IEEE INFOCOM*, pages 775–784, 2000.

[8] D. Braginsky and D. Estrin. Rumor Routing Algorithm For Sensor Networks. In *WSNA'02*, Atlanta, Georgia, USA, September 2002.

[9] S. Brands and D. Chaum. Distance-Bounding Protocols (Extended Abstract). In T. Helleseth, editor, *EUROCRYPT'93, Lecture Notes in Computer Science 765*, pages 344–359, 1993.

[10] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva. A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols. In *ACM MOBICOM*, pages 85–97, 1998.

[11] V. Capellano. Performance Improvement of a 50km Acoustic Transmission through Adaptive Equalization and Spatial Diversity. In *Oceans'97*, Nova Scotia, Canada, 1997.

[12] V. Capellano, G. Loubet, and G. Jourdain. Adaptive Multichannel Equalizer for Underwater Communications. In *Oceans'96*, Ft. Lauderdale, FL, USA, 1996.

[13] M. Cooper and M. Goldburg. Intelligent antennas: Spatial division multiple access. *Annual Review of Communications*, pages 999–1002, 1996.

[14] J. Deng, R. Han, and S. Mishra. Intrusion Tolerance and Anti-Traffic Analysis Strategies for Wireless Sensor Networks. In *IEEE International Conference on Dependable Systems and Networks (DSN)*, pages 594–603, 2004.

[15] W. Du, J. Deng, Y. S. Han, and P. K. Varshney. A Pairwise Key Pre-distribution Scheme for Wireless Sensor Networks. In *ACM CCS*, pages 42–51, 2003.

[16] L. Eschenauer and V. D. Gligor. A Key-Management Scheme for Distributed Sensor Networks. In *ACM CCS*, pages 41–47, 2002.

[17] D. K. et al. Spatial modulation experiments in the underwater acoustic channel. *IEEE Journal of Oceanic Engineering*, submitted 2003.

[18] K. Fall. A Delay Tolerant Networking Architecture for Challenged Internets. In *ACM SIGCOMM 2003*, August 2003.

[19] G. J. Foschini and M. J. Gans. On limits of wireless communication in a fading environment when using multiple antennas. *Wireless Personal Communications*, 6:311–335, March 1998.

[20] A. Ghrayeb, G. B. Giannakis, A. Goldsmith, S. Jafar, N. Jindal, R. A. Valenzuela, S. Vishwanath, and S. Zhou. The theory and practice of mimo: Promises and realities. In *Proc. of Global Telecommunications Conference*, Dallas, TX, 2004, Conference Tutorial.

[21] J. Heidemann, Y. Li, A. Syed, J. Wills, and W. Ye. Underwater sensor networking: Research challenges and potential applications. *USC/ISI Technical Report ISI-TR-2005-603*, 2005.

[22] W. R. Heinzelman, J. Kulik, and H. Balakrishnan. Adaptive Protocols for Information Dissemination in Wireless Sensor Networks. In *Mobicom'99*, Seattle, Washington, USA, August 1999.

[23] L. Hu and D. Evans. Using Directional Antennas to Prevent Wormhole Attacks. In *Network and Distributed System Security Symposium (NDSS)*, 2004.

[24] Y.-C. Hu, A. Perrig, and D. B. Johnson. Packet Leashes: A Defense against Wormhole Attacks in Wireless Networks. In *IEEE INFOCOM*, 2003.

[25] C. Intanagonwiwat, R. Govindan, and D. Estrin. Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks. In *ACM MOBICOM*, pages 56–67, 2000.

[26] D. B. Johnson and D. A. Maltz. Dynamic Source Routing in Ad Hoc Wireless Networks. In T. Imielinski and H. Korth, editors, *Mobile Computing*, volume 353, pages 153–181. Kluwer Academic Publishers, 1996.

[27] A. Kaya and S. Yauchi. An Acoustic Communication System for Subsea Robot. In *Oceans'89*, volume Vol.3, pages 765–770, September 1989.

[28] D. B. Kilfoyle and A. B. Baggeroer. The State of the Art in Underwater Acoustic Telemetry. *IEEE Journal of Oceanic Engineering*, OE-25(5):4–27, January 2000.

[29] J. Kong, Z. Ji, W. Wang, M. Gerla, R. Bagrodia, and B. Bhargava. Low-cost Attacks against Packet Delivery, Localization and Synchronization Services in Under-Water Sensor Networks. In *Fourth ACM Workshop on Wireless Security (WiSe)*, 2005.

[30] X. Ma and G. B. Giannakis. Maximum diversity transmissions over doubly-selective wireless channels. *IEEE Trans. on Information Theory*, 49(7):1832–1840, July 2003.

[31] S. Mascolo, C. Casetti, M. Gerla, M. Y. Sanadidi, and R. Wang. TCP Westwood: Bandwidth Estimation for Enhanced Transport over Wireless Links. In *ACM MOBICOM*, pages 287–297, 2001.

[32] D. Niculescu and B. Nath. Ad hoc positioning system (APS) using AoA. In *IEEE INFOCOM*, 2003.

[33] R. Ogier, M. Lewis, and F. Templin. Topology Dissemination Based on Reverse-Path Forwarding (TBRPF). `http://www.ietf.org/internet-drafts/draft-ietf-manet-tbrpf-07.txt`, March 2003.

[34] C. Ozturk, Y. Zhang, and W. Trappe. Source-Location Privacy in Energy-Constrained Sensor Network Routing. In *ACM SASN*, pages 88–93, 2004.

[35] C. E. Perkins and P. Bhagwat. Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers. In *ACM SIGCOMM*, pages 234–244, 1994.

[36] C. E. Perkins and E. M. Royer. Ad-Hoc On-Demand Distance Vector Routing. In *IEEE WMCSA'99*, pages 90–100, 1999.

[37] A. Perrig, R. Szewczyk, V. Wen, D. E. Culler, and J. D. Tygar. SPINS: security protocols for sensor netowrks. In *ACM MOBICOM*, pages 189–199, 2001.

[38] N. Priyantha, A. Chakraborty, and H. Padmanabhan. The Cricket Location Support System. In *ACM MOBICOM*, pages 32–43, 2000.

[39] J. G. Proakis, E. M. Sozer, J. A. Rice, and M. Stojanovic. Shallow Water Acoustic Networks. *IEEE Communications Magazine*, pages 114–119, November 2001.

[40] T. S. Rappaport. *Wireless Communications: Principles and Practice*. Prentice Hall, 1996.

[41] Y. Sankarasubramainam, Ö. B. Akan, and I. F. Akyildiz. Esrt:event-to-sink reliable transport in wireless sensor networks. In *The 4th ACM International Syspossium on Mobile Ad Hoc Networking and Computing (MobiHoc'03)*, Annapolis,Maryland,USA, June 2003.

[42] A. Savvides, C.-C. Han, and M. B. Srivastava. Dynamic Fine-Grained Localization in Ad-Hoc Networks of Sensors. In *ACM MOBICOM*, pages 166–179, 2001.

[43] E. M. Sozer, M. Stojanovic, and J. G. Proakis. Undersea Acoustic Networks. *IEEE Journal of Oceanic Engineering*, OE-25(1):72–83, January 2000.

[44] M. Stojanovic, J. Catipovic, and J. G. Proakis. Phase Coherent Digital Communication for Underwater Acoustic Channels. *IEEE Journal of Oceanic Engineering*, Vol. 19(1):100–111, January 1994.

[45] M. Suzuki, K. Nemoto, T. Tsuchiya, and T. Nakanishi. Digital Acoustic Telemetry of Color Video Information. In *Oceans'89*, pages 693–696, September 1989.

[46] I. E. Telatar. Capacity of multi-antenna Gaussian channels. *Bell Laboratories Technical Memorandum*, 1995.

[47] L. Tong, Q. Zhao, and G. Mergen. Multipacket reception in random access wireless networks: From signal processing to optimal medium access control. *IEEE Communications Magazine*, 39(11):108–112, Nov. 2001.

[48] S. Čapkun, L. Buttyán, and J.-P. Hubaux. SECTOR: Secure Tracking of Node Encounters in Multi-hop Wireless Networks. In *ACM Workshop on Security of Ad Hoc and Sensor Networks (SASN)*, pages 21–32, 2003.

[49] S. Čapkun and J.-P. Hubaux. Secure Positioning of Wireless Devices with Application to Sensor Networks. In *IEEE INFOCOM*, 2005.

[50] C.-Y. Wan, A. T. Campbell, and L. Krishnamurthy. PSFQ: A Reliable Transport Protocol for Wireless Sensor Networks. In *WSNA'02*, Atlanta, Georgia, USA, September 2002.

[51] C.-Y. Wan, S. B. Eisenman, and A. T. Campbell. CODA: Congestion Detection and Avoidance in Sensor Networks. In *ACM SenSys'03*, Los Angeles, California, USA, November 2003.

[52] Z. Wang and G. B. Giannakis. Wireless multicarrier communications: Where Fourier meets Shannon. *IEEE Signal Processing Magazine*, pages 29–48, May 2000.

[53] G. G. Xie and J. Gibson. A Networking Protocol for Underwater Acoustic Networks. Technical Report TR-CS-00-02, Department of Computer Science, Naval Postgraduate School, December 2000.

[54] F. Ye, H. Luo, J. Cheng, S. Lu, and L. Zhang. A Two-tier Data Dissemination Model for Large-scale Wireless Sensor Networks. In *MOBICOM'02*, Atlanta, Georgia, USA, September 2002.

[55] F. Ye, G. Zhong, S. lu, and L. Zhang. GRAdient Broadcast: A Robust Data Delivery Protocol for Large Scale Sensor Networks. *ACM Wireless Networks(WINET)*, Vol.11(2), March 2005. The earlier version appears in IPSN2003.

[56] W. Ye, J. Heidemann, and D. Estrin. An Energy-Efficient MAC Protocol for Wireless Sensor Networks. In *IEEE Infocom*, New York, NY, June 2002.