Challenges: Building Scalable Mobile Underwater Wireless Sensor Networks for Aquatic Applications

Jun-Hong Cui[1], Jiejun Kong[2], Mario Gerla[2], Shengli Zhou[3]
jcui@cse.uconn.edu, jkong, gerla@cs.ucla.edu, shengli@engr.uconn.edu
[1] Computer Science & Engineering Department, University of Connecticut, Storrs, CT 06029
[2] Computer Science Department, University of California, Los Angeles, CA 90095
[3] Electrical & Computer Engineering Department, University of Connecticut, Storrs, CT 06029

Abstract—

Large-scale mobile Underwater Wireless Sensor Network (UWSN) is a novel networking paradigm to explore aqueous environments. However, the characteristics of mobile UWSNs, such as low communication bandwidth, large propagation delay, floating node mobility, and high error probability, are significantly different from ground-based wireless sensor networks. The novel networking paradigm poses inter-disciplinary challenges that will require new technological solutions. In particular, in this article we adopt a top-down approach to explore the research challenges in mobile 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 mobile 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 earth is water planet. 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. Recently, there has been a growing interest in monitoring aqueous environments (including oceans, rivers, lakes, ponds and reservoirs, etc.) for scientific exploration, commercial exploitation and attack 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 scalable UWSN provides a promising solution for efficiently exploring and observing the aqueous environments 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 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 aqueous systems are 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, and we refer UMSN with mobile sensors as **mobile UWSN**.

In a mobile UWSN, the sensor mobility can bring two major benefits: (1) Mobile sensors injected in the current in relative large numbers can help to track changes in the water mass, thus provide 4D (space and time) environmental sampling. 4D sampling is required by many aquatic systems studies, such as estuary monitoring [5]; the alternative is to drag the sensors on boats and or on wires and carry out a large number of repeated experiments. This latter approach would take much more time and possibly cost. The multitude of sensors helps to provide extra control on redundancy and granularity. (2) Floating sensors can help to form dynamic monitoring coverage and increase system reusability. In fact, through a "bladder" apparatus one can dynamically control the depth of the sensor deployment, and force resurfacing and recovery when the battery is low or the mission is over. In traditional aquatic monitoring or surveillance applications, sensors are usually fixed to the sea floor or attached to pillars or surface buoys, and sensors with computational power are usually of big size. Thus, the sensor replacement and recovery cost is very high, as also results in low system reusability.

To summarize, 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.

Mobile UWSN is a novel technique. Compared with ground-based sensor networks, mobile UWSNs have to employ acoustic communications, since radio does not work well in underwater environments. Due to the unique features of large latency, low bandwidth, and high error rate, underwater acoustic channels bring many challenges to the protocol design. Moreover, in mobile UWSNs, the majority of underwater sensor nodes (except some fixed nodes equipped on surface-level buoys) are mobile due to water currents. This node mobility is another critical issue to consider in the system design. Furthermore, mobile UWSNs are significantly different from existing small-scale Underwater Acoustic Networks (UANs) due to its large scale and dense sensor deployment. Correspondingly, some new tasks such as localization and multiple access are demanded in mobile UWSNs.

In this article, 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 mobile UWSNs and pinpoint the crucial principle of the network architecture design. Then based on the wide range system requirements of various aquatic applications, we 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 mobile 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. According to [6], nearly no research and commercial system can exceed 40 `km` × `kbps` as the maximum attainable `range` × `rate` product. 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 such as path loss, noise, multi-path, and Doppler spread. All these factors cause high bit-error and delay variance.

In short, underwater acoustic channels feature large propagation delay, 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 Mobile UWSNs and Ground-Based Sensor Networks*

A mobile 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 underwater environments. 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. Specially, 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.

Node 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, the 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 [2]. Therefore, if a network protocol proposed for ground-based sensor networks does not consider mobility for the majority of sensor nodes, it would likely fail when directly cloned for aquatic applications.

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

C. Current Underwater Network Systems and Their Limitations

A scalable and mobile Underwater Wireless Sensor Network (UWSN) is a major step forward with respect to existing small-scale Underwater Acoustic Networks (UANs) [9] [8]. The major differences between UANs and mobile UWSNs lie in the following dimensions:

Scalability: A mobile 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 mobile 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 mobile 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 mobile UWSNs to handle self-organized sensors with slow data rates and high dispersion rates.

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 mobile UWSNs, localization is required because the 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 consider improving the localization accuracy, which could be significantly affected by poor acoustic channel quality and node mobility, which introduces more error when a cooperative localization approach (involving multiple nodes) is employed.

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

D. Difference from Other Survey Articles in Underwater Sensor Networks

Underwater sensor network is a very new research area. Recent articles [1] and [4] provide good surveys on this area. Specially, [1] takes a similar approach to this article to review research problems along the protocol stack (from bottom to up). The key difference between this article and [1] is that we address "mobile" UWSN instead of "static" UWSN. In [1], the authors assume most sensors are anchored to the sea floor. This kind of network setting is surely valid for a range of applications, especially for applications where mobile sensors are impossible. For example, in global seismic prediction, it is unrealistic to deploy mobile sensors in a basin scale (thousands of kilometers) area. Moreover, this kind of applications usually do not need very dense data sampling. On the other hand, we do admit that due to the harsh underwater conditions, some applications may need some intermediate solutions. One example is seismic monitoring for oil extraction from underwater fields [4], in 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.

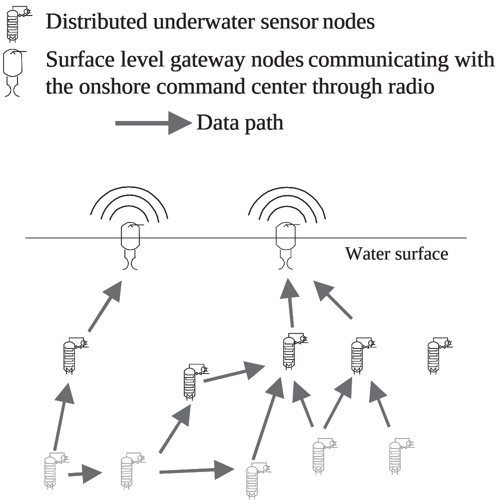

Fig. 1. An illustration of the mobile UWSN architecture for long-term non-time-critical aquatic monitoring applications

Clearly, this network setting does not have sensor node mobility. Besides seismic monitoring, [4] also briefly discussed the scenario of underwater robot flocks, which has "active" mobility, different from the "passive" mobility in mobile UWSNs. We prefer to classify this network scenario into small scale UANs.

III. TWO NETWORKING ARCHITECTURES FOR MOBILE 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 roughly 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, 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 mobile UWSN architecture for each type of aquatic applications, and pinpoint the key design issues in each of the mobile UWSN architectures.

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

Fig. 1 illustrates the mobile UWSN architecture for long-term non-time-critical aquatic monitoring applications. In this type of network, sensor nodes are densely deployed to cover a spacial continuous monitoring area[1]. 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.

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 (In WHOI Micro-Modem, the transmit power is 10 Watts, and the receive power is 80 milliwatts. Note that Micro-Modem is designed for medium range (1 to 10 km) acoustic communications. For the very short range communication in mobile UWSNs, power efficient acoustic modems are yet to be developed.) 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 mobile UWSNs for long-term aquatic monitoring, localization is a must-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 crossing 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. Self-relocation obviously needs some buoyancy control, which is very energy-consuming. Thus, a practical mobile UWSN system design has to well deal with the trade-off between energy efficiency and self-reorganizability.

Another interesting problem in such mobile UWSN systems is energy harvesting. Since sensor nodes are deployed in underwater environments, which are quite different from ground environments, many natural questions may be brought up: Are there any new means to easily generate power? Could water current movement be utilized for battery recharging? Are micro hydroelectric generator possible? Could solar energy on the water surface be exploited? Due to the young age of the underwater wire-

---

[1] Depending the applications, we expect that the distance between nodes ranges from 1m to 100m and a typical coverage is in the range of $[100, 10000] m^2$. For applications requiring very large areas, it is necessary to deploy multiple mobile UWSNs to form a hierarchical network.

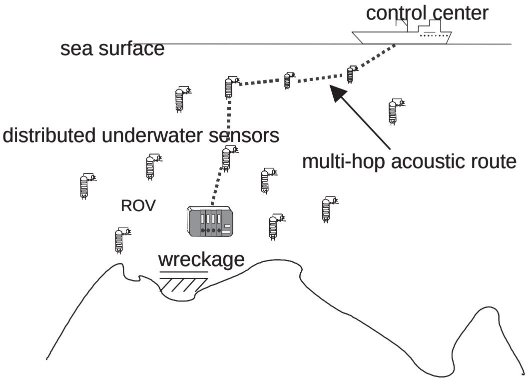

Fig. 2. An illustration of the mobile UWSN architecture for short-term time-critical aquatic exploration applications

less sensor network area, these interesting questions are yet to be answered.

Lastly, reliable, resilient, and secure data transfer is required to ensure a robust observing system.

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

In Fig. 2, we show a civilian scenario of the mobile UWSN architecture for short-term time-critical aquatic exploration applications. Assume a ship wreckage & accident investigation team wants 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 mobile underwater wireless sensor network, as shown in Fig. 2, the investigation team can control the ROV remotely. The self-reconfigurable 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-the-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 data rates ranging from very small (e.g., send an alarm that a submarine was detected) to relatively high (e.g., send images, 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 that the link bandwidth can reach up to 0.5Mbps at the distance of 60 meters [6]. Such high data rate is suitable to deliver even multimedia data.

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

- Real-time data transfer is more of concern.
- Energy saving becomes a secondary issue.
- Localization is not a must-do task.

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

IV. RESEARCH CHALLENGES IN MOBILE UWSN 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. For the ease of presentation, in this section, we use "UWSN" for the shorthand of "mobile UWSN".

A. *Security, Resilience and Robustness*

A self-organizing sensor network needs more protections than cryptography due to the limited energy, computation, and communication capabilities of sensor nodes. 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 sensor networks independent of cryptographic protections.

In a UWSN, due to the unique characteristics of underwater acoustic channels, denial-of-service attacks are lethal. In particular, wormhole attack (in which an attacker records a packet at one location in the network, tunnels the data to another location, and replays the packet there) 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 [7], 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 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-based sensor networks. Many existing wormhole countermeasures proposed for radio networks exploit this fact to bound the distance between a sender and its receiver. Thus, to protect against wormhole attacks in UWSNs, new techniques are demanded.

Another 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) [3]. DTN includes the use of intermediate store and forward proxies. If the data sink (i.e., the command center) 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 were 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. However, 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) [11], 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. Hop-by-hop, data packets are finally delivered to the data sink reliably. In PSPQ, ARQ (Automatic Repeat Request) is used for per-hop communication. However, due to the long propagation delay of acoustic signals, in UWSNs, ARQ would cause very low channel utilization. One possible solution to solve the problem is to investigate erasure coding schemes, which, though introducing additional overhead, can effectively avoid retransmission 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 topic 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, the congestion control problem is thoroughly investigated in CODA (Congestion Detection and Avoidance) [12]. 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 apply, since it provides a good compromise between fast reaction (with open) and efficient steady state regulation (with closed). Considering the poor quality of acoustic channels, 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 systems 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. They are mainly designed for stationary networks and 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 dramatically even with small displacements. Thus, the existing routing algorithms using query flooding designed for ground-based sensor networks are no longer feasible in UWSNs.

There are also many routing protocols proposed for ground-based mobile ad hoc networks. These protocols generally fall into two categories: proactive routing and reactive routing (aka., on demand routing). In proactive ad hoc routing protocols, the cost of proactive neighbor detection could be very expensive because of the large scale of UWSNs. On the other hand, in on demand routing, routing operation is triggered by the communication demand at sources. In the phase of route discovery, the source seeks to establish a route towards the destination by flooding a route request message, which would be very costly in large scale UWSNs.

With no proactive neighbor detection and with less flooding, it is a big challenge to furnish multi-hop packet delivery service in UWSNs with node mobility requirement. One possible direction is to utilize location information to do geo-routing, which proves to be very effective in handling mobility. However, 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 for every underwater node to know its current position and the synchronized time with respect to other coordinating nodes. Due to quick absorption of high-frequency radio wave, Global Positioning System (GPS) does not work well under the water. So far, to our best knowledge, a low-cost positioning and time-synchronization system while with high precision like GPS for ground-based sensor nodes is not yet available to underwater sensor nodes. Thus, it is expected that UWSNs must rely on *distributed GPS-free localization or time synchronization scheme*, which is referred to cooperative localization or time synchronization. To realize this type of approaches in a network with node mobility, the key problem is the range and direction measurement process. 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 is no longer feasible as the commonly available RF signal fails under the water. Receiver-signal-strength-index (RSSI) 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 require directional transmission/reception devices, which could be explored, though they usually incur non-trivial extra cost.

Promising approaches may include acoustic-only Time-of-Arrival (ToA) approaches (e.g. measuring round-trip time by actively bouncing the acoustic signal) 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 characteristics of the underwater acoustic channel, especially limited bandwidth and high propagation delays, pose unique challenges for media access control (MAC) that enables multiple devices to share a common wireless medium in an efficient and fair way. 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. Contention based protocols include random access (ALOHA, slotted ALOHA), carrier sense access (CSMA), and collision avoidance with handshaking access (MACA, MACAW), 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 [8] [1]. One possible direction is to explore ALOHA/slotted ALOHA in UWSNs since satellite networks, which 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 due to the excessive propagation delay. As a result, CDMA has been highlighted as a promising multiple access technique for underwater acoustic networks [8] [1]. If multiple antenna elements are deployed at certain relay or access points, then spatial division multiple access (SDMA) is a viable choice. 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.

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, last two decades only witness 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. Following the deployment of coherent systems, performance improvement has been moderate, and mostly only due to receiver enhancement. Substantial innovations are needed at the physical layer to robustify the system performance and offer significantly higher data rate for underwater communication networks [10].

V. SUMMARY

In this article, we call for the attention to build scalable and distributed mobile UWSNs for aquatic applications. We identify the unique characteristics of mobile 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 mobile UWSNs is an inter-disciplinary challenge requiring integration of acoustic communications, signal processing and mobile network design.

REFERENCES

[1] 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.

[2] W. Broecker and T.-H. Peng. Tracers in the sea. *Eldigio Press, Lamont Doherty Earth Observatory of Columbia University, Palisades, NY*, page 689, 1982.

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

[4] 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.

[5] D. A. Jay, W. R. Geyer, R. J. Uncles, J. Vallino, J. Largier, and W. R. Boynton. A review of recent developments in estuarine scalar flux estimation. *Estuaries*, 20(2):262–280, 1997.

[6] 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.

[7] 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.

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

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

[10] M. Stojanovic. Retrofocusing techniques for high rate acoustic communications. *Journal of the Acoustical Society of America*, 117(1):1173–1185, March 2005.

[11] 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.

[12] 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.