The Challenges of Building Scalable Mobile Underwater Wireless Sensor Networks for Aquatic Applications

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Abstract

The 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 interdisciplinary 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 proceed roughly 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 interdisciplinary efforts of acoustic communications, signal processing, and mobile acoustic network protocol design.

The Earth is a water planet. The largely unexplored vastness of the ocean, covering about two-thirds of the surface of the Earth, has fascinated humans for as long as we have kept 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 protection from attack. The ideal vehicle for this type of extensive monitoring is a networked underwater wireless sensor distributed system, referred to as the Underwater Wireless Sensor Network (UWSN). A scalable UWSN will provide a promising solution for efficiently exploring and observing the aqueous environments which operate under the following constraints:

• Unmanned underwater exploration: Underwater conditions are not suitable for human exploration. High water pressure, unpredictable underwater activities, and the vast size of underwater areas are major reasons for unmanned exploration.

• 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 enable us to acquire adequate knowledge about physical events happening in the volatile underwater environment.

• Tetherless underwater networking: The Internet is expanding to outer space and underwater. Undersea explorer Dr. Robert Ballard has used the 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 costs with regard to deployment, maintenance, and device recovery to cope with volatile undersea conditions.

• 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 3D underwater space, each underwater sensor can monitor and detect environmental events locally. This can be accomplished with fixed position sensors. However,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 to a UMSN with mobile sensors as a mobile UWSN.

In a mobile UWSN, sensor mobility can bring two major benefits:

• Mobile sensors injected in the current in relatively large numbers can help to track changes in the water mass, thus providing 4D (space and time) environmental sampling, which is required by many aquatic systems studies, such as estuary monitoring [1]. 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 require much more time and possibly cost. The multitude of sensors helps to provide extra control on redundancy and granularity.

• Floating sensors can help to enable dynamic monitoring coverage and increase system reusability. In fact, through a

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"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 large size. Thus, the sensor replacement and recovery costs are very high, and this also results in low system reusability.

To summarize, the self-organizing network of mobile sensors provides better support with regard to sensing, monitoring, surveillance, scheduling, underwater control, and fault tolerance. Hence, we are equipped with 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 (with the exception of 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 their large-scale and dense sensor deployment. Correspondingly, some new tasks such as localization and multiple access are required in mobile UWSNs.

In the rest of this article, we first review the characteristics of acoustic communications and some related work on ground-based wireless sensor networks and underwater acoustic networks, identify the distinct features of mobile UWSNs, and pinpoint the crucial principle of the network architecture design. Then, based on the wide-ranging 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 proceeding 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 a scalable mobile UWSN is a challenge that must be answered by interdisciplinary efforts among acoustic communications, signal processing, and mobile acoustic network protocol design.

Background and Related Work

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 an underwater acoustic channel is about 1.5×10^3 m/s, which is five orders of magnitude lower than the radio propagation speed (3×10^8 m/s). 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 30 kHz. According to [2], nearly no research nor commercial system can exceed 40 km × kb/s as the maximum attainable `range` × `rate` product.

The bandwidth of underwater acoustic channels operating over several kilometers is about several tens of kilobits per second, while short-range systems over several tens of meters can reach hundreds of kilobits per second. In addition to these inherent properties, underwater acoustic communication channels are affected by many factors such as path loss, noise, multipath, 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.

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 delays, which brings big challenges in reliable data transfer and traffic congestion control. 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 limited 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, have low or medium mobility due to water currents and other underwater activities. From empirical observations, underwater objects may move at speeds of 2–3 knots (or 3–6 km/h) in a typical underwater condition [3]. 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.

Current Underwater Network Systems and Their Limitations

A scalable and mobile UWSN is a major step forward with respect to existing small-scale UANs [4, 5]. The major differences between UANs and mobile UWSNs lie in the following factors.

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 that relies on data-collecting strategies like remote telemetry or assums that communication is point-to-point. In remote telemetry, data are

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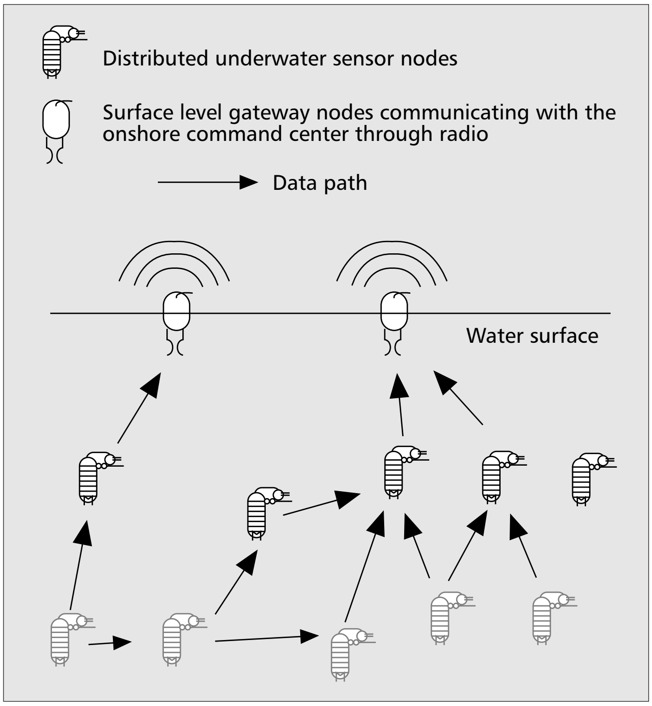

■ Figure 1. *An illustration of the mobile UWSN architecture for long-term non-time-critical aquatic monitoring applications.*

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 for meeting the demands of high-precision applications. In UANs, where point-to-point communication is assumed, sensor nodes are usually sparsely distributed (in several kilometers) and thus no multi-access technique is needed; while in mobile UWSNs, sensor nodes are densely deployed in order to achieve better spatial coverage and 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 no multiple mobile sensors are 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 reorganize 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 OPS 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 be directly applied to a mobile UWSN.

Differences with Other Survey Articles on Underwater Sensor Networks

Underwater sensor networks represent a very new research area. Recent articles [6, 7] provide good surveys on this area. Specially, [6] takes a similar approach to this article in reviewing research problems along the protocol stack (from bottom to top). The key difference between this article and [6] is that we address "mobile" UWSN instead of "static" UWSN. In [6] 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, these 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 [7], 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. Clearly, this network setting does not have sensor node mobility. Besides seismic monitoring, in [7] the scenario of underwater robot flocks, which has "active" mobility as opposed to the "passive" mobility in mobile UWSNs, is also briefly discussed. We prefer to classify this network scenario into small-scale UANs.

Two Networking Architectures for Mobile UWSNs

In general, depending on the permanent versis on-demand placement of the sensors, the time constraints imposed by the applications, and the volume of data being retrieved, we can 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 falling 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, antisubmarine military missions, lost treasure discovery, and so forth. 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.

Mobile UWSN for Long-Term Non-Time-Critical Aquatic Monitoring

Figure 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 spatial continuous monitoring area.[1] Data are collected by local sensors and relayed by intermediate sensors, and then finally reach the surface nodes (equipped with both acoustic and RF modems), which can transmit data to the on-shore command center by radio.

Since this type of network is designed for long-term moni-

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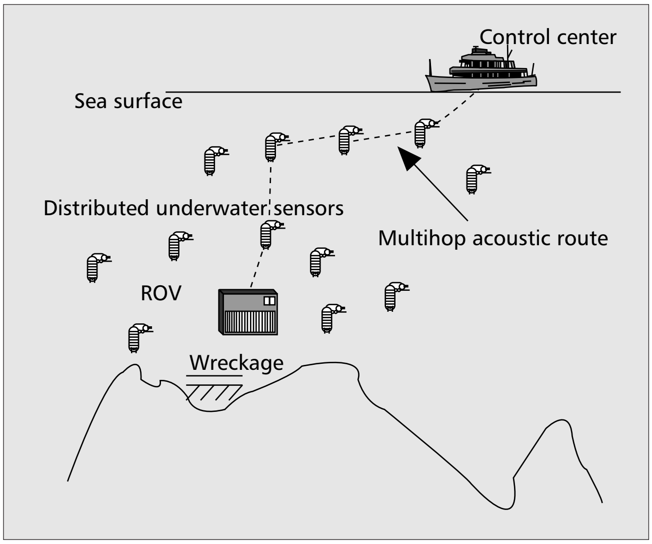

■ Figure 2. *An illustration of the mobile UWSN architecture for short-term time-critical aquatic exploration applications.*

toring tasks, 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 [8], the transmit power is 10 Watts, and the receive power is 80 mW. 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 power, they should be able to pop up to the water surface for recharging, for which a simple air-bladder-like device would suffice.

Clearly, in mobile UWSNs for long-term aquatic monitoring, localization is a must-do task for locating 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 floating sensors have crossed 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 manual redeployment. Self-relocation obviously needs some buoyancy control, which is very energy-consuming. Thus, a practical mobile UWSN system design has to deal effectively 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 raised: Are there any new means to easily generate power? Could water current movement be utilized for battery recharging? Are micro hydroelectric generators possible? Could solar energy on the water surface be exploited? Due to the young age of the underwater wireless sensor network area, these interesting questions are yet to be answered.

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

Mobile UWSN for Short-Term Time-Critical Aquatic Exploration

Figure 2 shows a civilian scenario of the mobile UWSN architecture for short-term time-critical aquatic exploration applications. Assume a ship-wreckage and accident-investigation team wants to identify the target venue. Existing approaches usually employ tethered wire/cable to a remotely operated vehicle (ROV). When the cable is damaged, the ROV is out of control or not recoverable. In contrast, by deploying a mobile UWSN, 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 a 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 stealth technologies, the acoustic signature of a modem 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 ROY 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 it is limited by acoustic physics and coding technology, high-data-rate networking can only be realized in the high-frequency acoustic band for underwater communication. It was demonstrated by empirical implementations that the link bandwidth can reach up to 0.5 Mb/s at a distance of 60 m [2]. Such a 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 short-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.

Research Challenges in Mobile UWSN Design

In this section we identify the design challenges along the network protocol stack in a top-down manner. It is clear that, at each layer, there are many critical problems awaiting solutions. For ease of presentation, in this section we use "UWSN" for the shorthand of "mobile UWSN."

[1] *Depending the applications, we expect that the distance between nodes ranges from 1 to l00 m, and typical coverage is in the range of [100, 10,000] m^2. For applications requiring very large areas, it is necessary to deploy multiple mobile UWSNs to form a hierarchical network.*

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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:

- Depleting a node's on-device resource (especially, draining battery by incurring extra computation and communication)
- 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, a 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 a great threat to underwater acoustic communications. Many countermeasures that have been proposed to stop wormhole attacks in radio networks are ineffectual in UWSNs. In [9] 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 a one-hop distance. Moreover, no signal, including those from the adversary, can propagate faster than 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 necessary.

Another problem that may arise in UWSNs is intermittent partitioning due to water turbulence, currents, ships and so forth. In fact, there may be situations where no connected path exists at any given time between the 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, delay-tolerant networking (DTN) [10]. 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.

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 Transmission Control Protocol (TCP), which is an end-to-end approach. We expect TCP performance to be problematic due to the high error rates incurred on the links, which were already encountered in wireless radio networks. However, in underwater environments, we have an additional problem: propagation time is much larger than transmission time, thus setting the stage for the well-known large *bandwidth* × *delay* product problem. Consider a path with 20 nodes spaced by 50 m with a rate of 500 kb/s 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 never be able to maintain the maximum rate. There are a number of techniques that can be used to render the TCP performance more efficient. However, the performance of these TCP variants in UWSNs is yet to be investigated.

Another method for reliable data transfer is the hop-by-hop approach, which is favored in wireless and error-prone networks, and is believed to be more suitable for sensor networks. Wan et al. designed Pump Slowly and Fetch Quickly (PSFQ) [11], which employs the hop-by-hop approach. In this protocol, a sender sends data packets 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, Automatic Repeat Request (ARQ) 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 above, real-time data transfer is desired for short-term time-critical aquatic exploration applications. The provision of time-constrained services is yet another tough research topic in the networking community, even for the Internet. In the Internet, User Datagram Protocol (UDP) 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, a UDP-like approach obviously does not work. In ground-based ad hoc networks and sensor networks, path redundancy is usually exploited in order 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.

Traffic Congestion Control

Congestion control is an important albeit 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 Congestion Detection and Avoidance (CODA) [12]. In CODA, there are two mechanisms for congestion control and avoidance: open-loop hop-by-hop backpressure and closed-loop multisource 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 the most likely one to reach the source directly. In the closed-loop multisource regulation, the source uses the ACKs from the sink to self-clock.

For UWSNs, we expect that a combination of open and closed loops may apply, since this 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 that 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 the source rate becomes. This will cause problems in underwater systems where random errors/loss may be prevalent. From received packet interarrival 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.

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Efficient Multihop Acoustic Routing

As 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 (also known as 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, the routing operation is triggered by the communication demand at the source. 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 multihop packet delivery service in UWSNs with the node-mobility requirement. One possible direction is to utilize location information for 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.

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 the quick absorption of high-frequency radio waves, Global Positioning System (GPS) does not work well underwater. 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 as 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. The receiver-signal-strength-index (RSSI) is vulnerable to acoustic interferences such as near-shore tide noise, near-surface ship noise, multipath, and Doppler frequency spread. Angle-of-arrival (AoA) systems require directional transmission/reception devices, which could be explored, although they usually incur nontrivial 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 the motion of water and the variation of temperature and pressure, also affects the speed of acoustic signals. Sophisticated signal processing will be needed to compensate for these sources of errors due to the water medium itself.

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:

- Scheduled protocols that avoid collision among transmission nodes
- 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 [5, 6]. 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 the 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 [5, 6]. If multiple antenna elements are deployed at certain relay or access points, then spatial division multiple access (SDMA) is a viable choice. As 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, so that each user is assigned a signature matrix that spreads over both space and time, thus extending the concept of temporal or spatial spreading.

Acoustic Physical Layer

Compared with their counterpart on radio channels, communications over underwater acoustic channels are severely rate-limited and performance-limited. That is caused by the inherent bandwidth limitation of acoustic links, the large delay spread, and the high time-variability due to slow sound propagation in underwater environments. As a result, unlike the rapid growth of wireless networks over radio channels, the last two decades have only witnessed two fundamental advances in underwater acoustic communications. One is the introduction of digital communication techniques, namely, noncoherent frequency shift keying (FSK), in the early 1980s, and the other is the application of coherent modulations, including phase shift keying (PSK) and quadrature amplitude modulation (QAM) in early 1990s [2]. Following the deployment of coherent systems, performance improvement has been moderate, and mostly only due to receiver enhancements [2]. Substantial innovations are needed at the physical layer to robustify the system performance and offer a significantly higher data rate for underwater communication networks.

A paradigm shift from current single-carrier transmissions

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and equalizations to multicarrier modulation in the form of orthogonal frequency division multiplexing (OFDM) is envisioned as a viable approach, as OFDM has had well-demonstrated success in broadband wireless radio systems. Another direction is to pursue multi-input multi-output (MIMO) techniques for substantial rate and performance improvement. Distributed MIMO is also possible if clustered single-antenna nodes could cooperate.

Summary

In this article, we have called attention to the building of scalable and distributed mobile UWSNs for aquatic applications. We have identified the unique characteristics of mobile UWSNs and presented two network architectures for different types of aquatic applications, identifying their key requirements in protocol design. Further, we have analyzed the design challenges of implementing the needed underwater networks. Following a top-down approach, we discussed the design challenges of each layer in the network protocol stack. Our study shows that designing mobile UWSNs is an interdisciplinary challenge requiring the integration of acoustic communications, signal processing, and mobile network design.

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