Underwater Sensor Networks: Applications, Advances, and Challenges

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This paper† examines the main approaches and challenges in the design and implementation of underwater wireless sensor networks. We summarize key applications and the main phenomena related to acoustic propagation, and discuss how they affect the design and operation of communication systems and networking protocols at various layers. We also provide an overview of communications hardware, testbeds, and simulation tools available to the research community.

Keywords: underwater communication, acoustic communication, underwater sensor networks, autonomous underwater vehicles, acoustic modems, energy efficiency, high latency, sound absorption, underwater testbeds, acoustic network simulation, medium access control, routing

1. Introduction

Wireless information transmission through the ocean is one of the enabling technologies for the development of future ocean-observation systems and sensor networks. Applications of underwater sensing range from oil industry to aquaculture, and include instrument monitoring, pollution control, climate recording, prediction of natural disturbances, search and survey missions and study of marine life.

Underwater wireless sensing systems are envisioned for stand-alone applications and control of autonomous underwater vehicles (AUVs), and as an addition to cabled systems. For example, cabled ocean observatories are being built on submarine cables to deploy an extensive fiber optic network of sensors (cameras, wave sensors, seismometers) covering miles of ocean floor (Tunnicliffe *et al.*, 2008). These cables can support communication access points, very much as cellular base stations are connected to the telephone network, allowing users to move and communicate from places where cables cannot reach. Another example are cabled submersibles, also known as remotely operated vehicles (ROVs). These vehicles, which may weigh more than ten metric tons, are connected to the mother ship by a cable that can extend over several kilometers and deliver high power to the remote end, along with high-speed communication signals. A popular example of an ROV/AUV tandem is the Alvin/Jason pair of vehicles deployed by the Woods Hole Oceanographic Institution in 1985 to discover Titanic. Such vehicles were also instrumental in the discovery of hydro-thermal vents, sources of extremely hot water on the bottom of

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deep ocean, which revealed forms of life different from any others previously known. The first vents were found in the late 1970s, and new ones are still being discovered. The importance of such discoveries is comparable only to space missions, and so is the technology that supports them.

Today, both the vehicle technology and the sensor technology are mature enough to motivate the idea of underwater sensor networks. To turn this idea into reality, however, one must face the problem of communications. Underwater communication systems today mostly use acoustic technology. Complementary communication techniques, such as optical (for example, Farr *et al.* (2010); Vasilescu *et al.* (2005)) and radio-frequency (for example, Cella *et al.* (2009)), or even electrostatic communication (for example, (Friedman *et al.*, 2010)), have been proposed for short-range links (typically 1–10m), where their very high bandwidth (MHz or more) can be exploited. These signals attenuate very rapidly, within a few meters (radio) or tens of meters (optical), requiring either high power or large antennas. Acoustic communications offer longer ranges, but are constrained by three factors: limited and distance-dependent bandwidth, time-varying multipath propagation, and low speed of sound (Urick, 1983; Stojanovic, 2007). Together, these constraints result in a communication channel of poor quality and high latency, thus combining the worst aspects of terrestrial mobile and satellite radio channels into a communication medium of extreme difficulty.

Among the first underwater acoustic systems was the submarine communication system developed in the United States around the end of the Second World War. It used analog modulation in the 8-11 kHz band (single-sideband AM). Research has since advanced, pushing digital modulation/detection techniques into the forefront of modern acoustic communications. At present, several types of acoustic modems are available commercially, typically offering up to a few kilobits per second (kbps) over distances up to a few kilometers. Considerably higher bit rates have been demonstrated, but these results are still in the domain of experimental research (e.g., (Carrascosa & Stojanovic, 2010; Roy *et al.*, 2009)).

With the advances in acoustic modem technology, research has moved into the area of networks. The major challenges were identified over the past decade, pointing once again to the fundamental differences between acoustic and radio propagation. For example, acoustic signals propagate at 1500 m/s, causing propagation delays as long as a few seconds over a few kilometers. With bit rates on the order of 1000 bps, propagation delays are not negligible with respect to typical packet durations—a situation very different from that found in radio-based networks. Moreover, acoustic modems are typically limited to half-duplex operation. These constraints imply that acoustic-conscious protocol design can provide better efficiencies than direct application of protocols developed for terrestrial networks (e.g., 802.11 or TCP). In addition, for anchored sensor networks, energy efficiency will be as important as in terrestrial networks, since battery re-charging hundreds of meters below the sea surface is difficult and expensive. Finally, underwater instruments (sensors, robots, modems, batteries) are neither cheap nor disposable. This fact may be the single most important feature that (at least for now) distinguishes underwater sensor networks from their terrestrial counterpart, and fundamentally changes many network design paradigms that are otherwise taken for granted.

While today there are no routinely operational underwater sensor networks, their development is imminent. Applications that motivate these developments are considered in Section 2. The underlying systems include fleets of *cooperating* autonomous vehicles (where vehicles have the capability to respond to one another, not only to the supervisory commands from a central authority that amounts to "switch from mission A to mission B"), and long-term deployable bottom-mounted sensor networks. Active research that fuels this development is the main subject of our paper. In Section 3, we describe key technical issues and new research approaches that come from revising traditional assumptions and exploiting cross-layer optimization both between adjacent layers and throughout the entire protocol stack, from the application to the physical link. We also describe the currently available hardware, and discuss tools for modeling and simulation, as well as testbeds.

2. Underwater Sensing Applications

The need to sense the underwater world drives the development of underwater sensor networks. Applications can have very different requirements: fixed or mobile, short or long-lived, best-effort or life-or-death; these requirements can result in different designs. We next describe different kinds of deployments, classes of applications, and several specific examples, both current and speculative.

(*a*) *Deployments*

Mobility and density are two parameters that vary over different types of deployments of underwater sensor networks. Here we focus on wireless underwater networks, although there is significant work in cabled underwater observatories, from the SOSUS (Sound Surveillance System) military networks in the 1950s, to the recent Ocean Observatories Initiative (Fairley, 2005).

Figure 1 illustrates several ways to deploy an underwater sensor network. Underwater networks are often *static*: individual nodes attached to docks, to anchored buoys or to the seafloor (as in the cabled or wireless seafloor sensors in Figure 1). Alternatively, *semi-mobile* underwater networks can be suspended from buoys that are deployed by a ship and used temporarily, but then left in place for hours or days (Shusta, 2010). (The moored sensors in Figure 1 may be short-term deployments.) The topologies of these networks are static for long durations, allowing engineering of the network topology to promote connectivity. However, network connectivity still may change due to small-scale movement (as a buoy precesses on its anchor) or to water dynamics (as currents, surface waves, or other effects change). When battery powered, static deployments may be energy constrained.

Underwater networks may also be *mobile*, with sensors attached to AUVs, low-power gliders, or unpowered drifters. Mobility is useful to maximize sensor coverage with limited hardware, but it raises challenges for localization and maintaining a connected network. Energy for communications is plentiful in AUVs, but it is a concern for gliders or drifters.

As with surface sensor networks, network density, coverage, and number of nodes are interrelated parameters that characterize a deployment. Underwater deployments to date are generally less dense, longer range, and employ significantly fewer nodes than terrestrial sensor networks. For example, the Seaweb deployment in 2000 involved 17 nodes spread over a 16 km^2 area with a median of 5 neighbors per node (Proakis *et al.*, 2001). Finally, as with remote terrestrial networks, con-

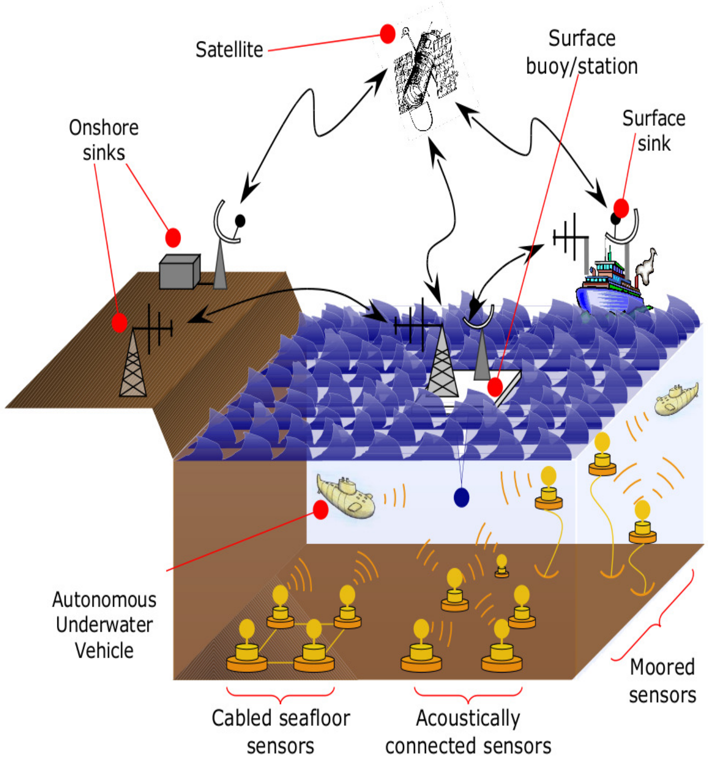


Figure 1. Deployments can be cabled, fixed and moored wireless, mobile (on AUVs), and can have different links to shore. Derived from Akyildiz *et al.* (2005, Figure 1).

nectivity to the Internet is important and can be difficult. Figure 1 shows several options, including underwater cables, point-to-point wireless, and satellite.

(*b*) *Application domains*

Applications of underwater networks fall into similar categories as for terrestrial sensor networks. *Scientific applications* observe the environment: from geological processes on the ocean floor, to water characteristics (temperature, salinity, oxygen levels, bacterial and other pollutant content, dissolved matter, etc.) to counting or imaging animal life (microorganisms, fish, or mammals). *Industrial applications* monitor and control commercial activities, such as underwater equipment related to oil or mineral extraction, underwater pipelines, or commercial fisheries. Industrial applications often involve control and actuation components as well. *Military and homeland security applications* involve securing or monitoring port facilities or ships in foreign harbors, de-mining, and communication with submarines and divers.

While the classes of applications are similar, underwater activities have traditionally been much more resource-intensive than terrestrial sensing. One can purchase commodity weather stations from US$100–1000, but deploying a basic underwater sensing system today starts at the high end and goes up, simply because of packaging and deployment costs. Scientific practice today often assumes sample collection and return for laboratory analysis, partly because the cost of getting data on-site requires maximizing the information returned. Inspired by low-cost terrestrial sensor networks (for example, (Heidemann *et al.*, 2006)) several research efforts (reviewed in Section 3f) today are exploring low-cost underwater options, but the fixed costs quickly rise for sensing in deeper water.

Finally, underwater sensing deployments occur over shorter periods (several hours), rather than days to months or years common in terrestrial sensing. Primary reasons are deployment cost coupled with a large area of interest, and battery limitations. Underwater deployments can be harsher than surface sensing, with biofouling requiring periodic maintenance. Powered or glider-based autonomous underwater vehicles may be coupled with buoys or anchored deployments.

Motivations for underwater sensor networks are similar to those for terrestrial sensornets: wireless communications reduces deployment costs, interactive data indicates whether sensing is operational or prompts corrective actions during collection, data analysis during collection allows attendant scientists to adjust sensing in response to interesting observations.

(*c*) *Examples*

There are many short-term or experimental deployments of underwater sensing or networking, here we only describe a few representative examples. Seaweb (Proakis *et al.*, 2001) is an early example of a large deployable network for potential military applications. Its main goal was to investigate technology suitable for communication with and detection of submarines. Deployments were in coastal ocean areas for multi-day periods.

MIT (Massachusetts Institute of Technology) and Australia's CISRO (Commonwealth Scientific and Industrial Research Organisation) explored scientific data collection with both fixed nodes and mobile autonomous robotic vehicles. Deployments have been relatively short (days), in very near-shore areas of Australia and the South Pacific (Vasilescu *et al.*, 2005).

By comparison, the Ocean Observatories Initiative is exploring large-scale cabled underwater sensing (Fairley, 2005). In this static, scientific application, cables provide power and communications to support long-term observations, but require significant long-term investments.

3. Underwater Communications and Networking Technology

In this section, we discuss a number of technology issues related to the design, analysis, implementation and testing of underwater sensor networks. We begin at the physical layer with the challenges of acoustic communication, then proceed to communications and networking layers, followed by a discussion on applications, hardware platforms, testbeds and simulation tools.

(*a*) *Physical Layer*

Outside water, the electromagnetic spectrum dominates communication, since radio or optical methods provide long-distance communication (meters to hundreds of kilometers) with high bandwidths (kHz to tens of MHz), even at low power. In contrast, water absorbs and disperses almost all electro-magnetic frequencies, making acoustic waves a preferred choice for underwater communication beyond tens of meters.

Propagation of acoustic waves in the frequency range of interest for communication can be described in several stages. Fundamental attenuation describes the power loss that a tone at frequency f experiences as it travels from one location to another. The first, basic stage, takes into account this fundamental loss that occurs over a transmission distance d. The second stage takes into account the site-specific loss due to surface-bottom reflections and refraction that occurs as sound speed changes with depth, and provides a more detailed prediction of the acoustic field around a given transmitter. The third stage addresses the apparently random changes in the large-scale received power (averaged over some local interval of time) which are caused by slow variations in the propagation medium (e.g., tides). These phenomena are relevant for determining the transmission power needed to close a given link. A separate stage of modeling is required to address the small-scale, fast variations of the *instantaneous* signal power.

Figure 2 illustrates the combined effect of attenuation and noise in acoustic communication, by plotting the quantity $[A(d,f)N(f)]^{-1}$ evaluated using the basic (ideal) propagation loss $A(d,f)$ and a typical power spectral density $N(f)$ of the background noise, which decays at 18 dB/decade (Urick, 1983; Stojanovic, 2007). This characteristic describes the signal-to-noise ratio (SNR) observed in a narrow band of frequencies around f. The figure clearly shows that high frequencies attenuate quickly at long distances, prompting most kilometer-range modems to operate below several tens of kHz, and suggests the existence of an optimal frequency for a given transmission range. In addition, it shows that the available bandwidth (and therefore the usable data rate) is reduced as the distance increases (Stojanovic, 2007). The design of a large-scale system begins with determining this frequency, and allocating a certain bandwidth around it.

Multipath propagation creates signal echoes that arrive with varying delays. Delay spreading depends on the system location, and can range from a few milliseconds to several hundreds of milliseconds. In a wideband system, this leads to a frequency selective channel transfer function as different frequency components may exhibit substantially different attenuation. The channel response and the instantaneous power often exhibit small-scale, fast variations, typically caused by scattering and the rapid motion of the sea surface (waves) or of the system itself. While large-scale variations influence power control at the transmitter, small-scale variations influence the design of adaptive signal processing algorithms at the receiver.

Directional motion causes additional time variation in the form of Doppler effect. A typical AUV velocity is on the order of a few m/s, while freely-suspended platforms can drift with currents at similar speeds. Because the sound propagates slowly, the ratio of the relative transmitter/receiver velocity to the speed of sound can be as high as 0.1%—an extreme value that implies the need for dedicated synchronization. This situation is in stark contrast with radio systems, where corresponding values are orders of magnitude smaller, and typically only the center frequency shifting needs to be taken into account.

To avoid the long delay spread and time-varying phase distortion, early systems focused on frequency modulation (FSK) and noncoherent (energy) detection. Although these methods do not make efficient use of the bandwidth, they are favored for robust communication at low bit rates (typically on the order of 100

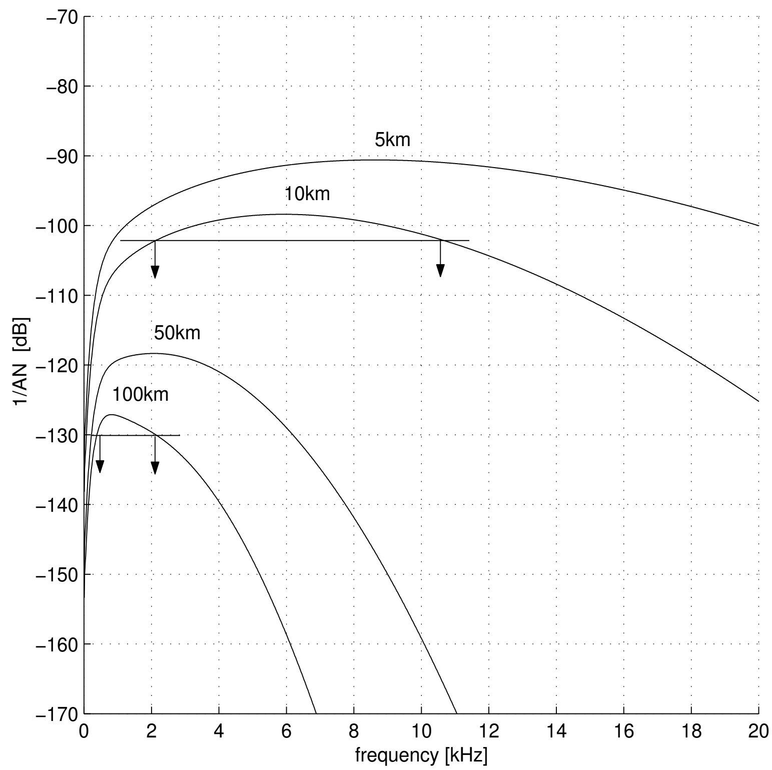


Figure 2. Narrow-band SNR as a function of frequency for varying transmission distances. Sound absorption limits the usable frequency range and makes it dependent on the transmission distance. In a typical acoustic system, the bandwidth is not negligible with respect to the center frequency (e.g., 5 kHz centered around 10 kHz).

bps over a few kilometers), and are used in both commercial modems such as the Telesonar series manufactured by Teledyne-Benthos (Green, 2010), and in research prototypes such as the micro-modem developed at the Woods Hole Oceanographic Institution (Singh *et al.*, 2009).

The development of bandwidth-efficient communication methods that use amplitude or phase modulation (QAM, PSK) gained momentum in the 1990s, after coherent detection was shown to be feasible on acoustic channels (Stojanovic *et al.*, 1993). Initial research focused on adaptive equalization and synchronization for single-carrier wideband systems, leading to real-time implementations that today provide "high-speed" communications at several kbps over varying link configurations (horizontal, vertical), as well as with AUVs.

Research on the physical layer is extremely active (Singer *et al.*, 2009). Single-carrier modulation/detection is being improved using powerful coding and turbo equalization (e.g., (Roy *et al.*, 2009)), while multi-carrier modulation/detection is considered as an alternative (e.g., (Carrascosa & Stojanovic, 2010), (Berger *et al.*, 2010)). Both types of systems are being extended to multi-input multi-output (MIMO) configurations that provide spatial multiplexing (the ability to send parallel data streams from multiple transmitters), and bit rates of several tens of kbps have been demonstrated experimentally.

Respecting the *physical* aspects of acoustic propagation is crucial for successful signal processing; understanding its *implications* is essential for proper network design. As Figure 2 illustrates, the available bandwidth decreases with distance, and this fact builds a strong case for multi-hopping, just as with radio-based networks on land. In an acoustic setting, dividing a long link into a number of shorter hops will not only allow power reduction, but will also allow the use of greater bandwidth (Stojanovic, 2007). A greater bandwidth yields a greater bit rate and shorter packets—as measured in seconds for a fixed number of bits per packet. While shorter bits imply less energy per bit, shorter packets imply fewer chances of collision on links with different, non-negligible delays. Both facts have beneficial implications on the network performance (and lifetime), provided that the interference can be managed.

These characteristics of the physical layer influence medium access and higher-layer protocol design. For example, the *same* network protocol may perform differently under a different frequency allocation—moving to a higher frequency region will cause more attenuation to the desired signal, but the interference will attenuate more as well, possibly boosting the overall performance. Also, propagation delay and the packet duration matter, since a channel that is sensed to be free may nonetheless contain interfering packets; their length will affect the probability of collisions and the efficiency of re-transmission (throughput). Finally, power control, coupled with intelligent routing, can greatly help to limit interference (Montana *et al.*, 2010).

(*b*) *Medium Access Control and Resource Sharing*

Multi-user systems need an effective means to share the communications resources among the participating nodes. In wireless networks, the frequency spectrum is inherently shared and interference needs to be properly managed. Several techniques have been developed to provide rules to allow different stations to effectively share the resource and separate the signals that coexist in a common medium.

In designing resource sharing schemes for underwater networks, one needs to keep in mind the peculiar characteristics of the acoustic channel. Most relevant in this context are long delays, frequency-dependent attenuation, and the relatively long reach of acoustic signals. In addition, the bandwidth constraints of acoustic hardware (and the transducer in particular) must also be considered.

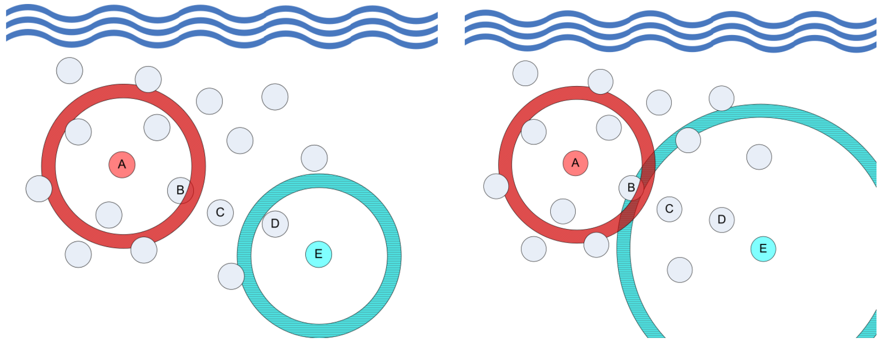
Signals can be deterministically separated in time (Time Division Multiple Access, TDMA) or frequency (FDMA). In the first case, users take turns accessing the medium, so that signals do no overlap in time and therefore interference is avoided. In FDMA, instead, signal separation is achieved in the frequency domain; although they may overlap in time, signals occupy disjoint parts of the spectrum. These techniques are extensively used in most communications systems, and have been considered for underwater networks as well (Sozer *et al.*, 2000). For example, due to acoustic modem limitations, FDMA was chosen for the early deployment of SeaWeb (Proakis *et al.*, 2001), even though the use of guard bands for channel separation leads to some inefficiency and this type of frequency channel allocation has very little flexibility (e.g., to accommodate varying transmission rates). TDMA can be more flexible, but requires synchronization among all users to make sure they access disjoint time slots. Many schemes and protocols are based on such an underlying time-division structure, which however needs some coordination and some guard times to compensate for inconsistencies in dealing with propagation delays.

Another quasi-deterministic technique for signal separation is Code Division Multiple Access (CDMA), in which signals that coexist in both time and frequency can be separated using specifically designed codes in combination with signal processing techniques. The price to pay in this case is a bandwidth expansion, especially acute with the narrow bandwidth of the acoustic channel (20kHz or less for typical hardware). CDMA-based medium access protocols with power control have been proposed for underwater networks (Pompili *et al.*, 2009), and have the advantages of not requiring slot synchronization and being robust to multipath fading.

While these deterministic techniques can be used directly in multi-user systems, data communication nodes typically use contention-based protocols, that prescribe the rules by which nodes decide when to transmit on a shared channel. In the simplest protocol, ALOHA, nodes just transmit whenever they need to (random access), and end-terminals recover from errors due to overlapping signals (called *collisions*) with retransmission. More advanced schemes implement *carrier-sense multiple access* (CSMA), a listen-before-transmit approach, with or without collision avoidance (CA) mechanisms, with the goal of avoiding transmission on an already occupied channel. While CSMA/CA has been very successful in radio networks, the latencies encountered underwater (up to several seconds) make it very inefficient underwater (even worse than ALOHA). In fact, while ALOHA is rarely considered in radio systems due to its poor throughput, it is a potential candidate for underwater networks when combined with simple CSMA features (Ahn *et al.*, 2011).

Two examples of protocols specifically designed for underwater networks following the CSMA/CA approach are DACAP (Peleato & Stojanovic, 2007) and T-Lohi (Syed *et al.*, 2008). DACAP is based on an initial signaling exchange in order to reserve the channel, thereby decreasing the probability of collision. T-Lohi exploits collision avoidance tones, whereby nodes that want to transmit signal their intention by sending narrowband signals, and proceed with data transmission if they do not hear tones sent by other nodes, providing lightweight signaling at the cost of greater sensitivity to the hidden-terminal problem (Syed *et al.*, 2008). T-Lohi also exploits high acoustic latency to count contenders in ways impossible with radios, allowing very rapid convergence (Syed & Heidemann, 2010).

While unsynchronized protocols are simpler, explicit coordination can improve the performance at the price of acquiring and maintaining a time reference. Although long propagation still causes inefficiency, synchronization allows protocols to exploit the space-time volume, intentionally overlapping packets in time while they remain distinct in space (Ahn *et al.*, 2011). Figure 3 gives an example of this principle, where unlike in near-instant radio communications, long acoustic latencies mean concurrent packets can be received successfully (Figure 3(a)) and packets sent at different times may collide (Figure 3(b)). Even though in most cases it is very difficult to operate such protocols in large networks, local synchronization can be achieved and used to improve efficiency. Several protocols have been proposed, that assume a common slotted structure accessed by the various nodes in the system. Early work exploited this effect, using centralized scheduling instead of random access to completely avoid collisions, although for static topologies and



(a) Same transmission time; no collision at B (b) Different transmission time but collision at B

Figure 3. Illustration of space-time volume (from (Ahn *et al.*, 2011, Figure 1)): long acoustic latencies mean that packet from A and E are successfully received at B and D in Figure 3(a), even though they are sent concurrently, while in Figure 3(b), packets collide at B even though sent at different times.

with additional signaling (Badia *et al.*, 2006). Slotted FAMA (Molins & Stojanovic, 2006) is a decentralized, CSMA-based protocol that uses synchronization to reduce the probability of collision, but is also subject to longer delays due to guard times. UWAN-MAC (Park & Rodoplu, 2007) is another such protocol, designed to minimize energy consumption through sleep modes and local synchronization.

A number of hybrid schemes have also been studied, in which two or more of the above techniques are combined (Kredo, Kurtis B. & Mohapatra, 2007).

(*c*) *The Network Layer, Routing, and Transport*

In large networks, it is unlikely that any pair of nodes can communicate directly, and multi-hop operation, by which intermediate nodes are used to forward messages towards the final destination, is typically used. In addition, multi-hop operation is beneficial in view of the distance-bandwidth dependence as discussed in Section 3a.

In this case, routing protocols are used to determine a variable route that a packet should follow through a topology. While there are many papers on ad hoc routing for wireless radio networks, routing design for underwater networks is still being actively studied. Early work on underwater routing includes (Pompili *et al.*, 2006), where distributed protocols are proposed for both delay-sensitive and delay-insensitive applications and allow nodes to select the next hop with the objective of minimizing the energy consumption while taking into account the specific characteristics of acoustic propagation as well as the application requirements. A geographic approach is proposed in (Zorzi *et al.*, 2008), where a theoretical analysis has shown that it is possible to identify an optimal advancement that the nodes should locally try to achieve in order to minimize the total path energy consumption. A similar scheme, where power control is also included in a cross-layer approach, was presented in (Montana *et al.*, 2010). Other approaches include pressure routing, where decisions are based on depth, which can be easily determined locally by means of a pressure gauge (Lee *et al.*, 2010).

An approach for data broadcasting has been proposed in (Nicopolitidis *et al.*, 2010), where an adaptive push system for the dissemination of data in underwater networks is proposed and shown to be able to work well despite the high latencies that are found in this environment.

The design of transport protocols in underwater acoustic networks is another critical issue. Protocols such as TCP are designed for low to moderate latencies, not the large fractions of a second commonly encountered in underwater networks, and limited bandwidth and high loss suggest that end-to-end retransmission will perform poorly. For example, Xie & Cui (2007) proposes a new transport protocol that employs erasure codes with variable block size to reliably transmit segmented data blocks along multihop paths. Network coding and forward-error correction can also be employed to cope with losses given long delays; coding benefits from optimizing coding and feedback (Lucani *et al.*, 2009). Different approaches such as Delay Tolerant Networking (Fall & Farrell, 2008) may be a better match to many underwater networks, by avoiding end-to-end retransmission and supporting very sparse and often disconnected networks.

Work on higher-layer data-dissemination protocols underwater has been sparse, with each deployment typically using a custom solution. One system is shown by Vasilescu *et al.* (2005), proposing synchronization and data collection, storage, and retrieval protocols for environmental monitoring.

Finally, an important issue is that of topology control, where nodes sleep to reduce energy while maintaining network connectivity. Although coordination and scheduling mechanisms can be used for this purpose, an interesting observation was made in Harris III *et al.* (2009), where it was recognized that acoustic devices, unlike radios, can actually be woken up by an incoming acoustic signal without additional hardware. With this feature, it is possible to wake up nodes on demand and to obtain a virtually perfect topology control mechanism. The SNUSE modem implements such a low-power wake-up circuit, which has been integrated into the MAC layer (Syed *et al.*, 2008), and the Benthos modem has a wake-up mode as well.

(*d*) *Network Services*

Of the many network services that are possible, *localization* and *time synchronization* have seen significant research because of their applicability to many scenarios. Localization and time synchronization are, in a sense, duals of each other: localization often estimates communication time-of-flight, assuming accurate clocks; time synchronization estimates clock skew, modeling slowly varying communication delays. Underwater, both pose the challenge of coping with long communications latency, and noisy, time-varying channels .

Time synchronization in wired networks dates back to the Network Time Protocol in the 1990s; wireless sensor networks prompted a resurgence of research a decade later with an emphasis on message and energy conservation through one-to-many or many-to-many synchronization (Elson *et al.*, 2002), and integration with hardware to reduce jitter (Ganeriwal *et al.*, 2003). Underwater time synchronization has built upon these ideas, revised to address challenges in slow acoustic propagation. Time-Synchronization for High Latency networks (TSHL (Syed & Heidemann, 2006)) showed that clock drift during message propagation dominates the error for acoustic channels longer than 500m. More recently, D-Sync incorporates Dopplershift estimation to account for the error due to node mobility, or due to water currents (Lu *et al.*, 2010).

Localization too has a history in wired and radio-based wireless networks, where node-to-node ranging (based on communications time-of-flight) and beacon proximity (reachability due to attenuation) are the two fundamental methods used to locate devices. As with time synchronization, localization protocols are often pairwise, or a beacon may broadcast to many potential receivers. Slow acoustic propagation *improves* localization, since each microsecond error in timing only corresponds to a 15mm error in location, However, bandwidth limitations make reducing message counts even more important than for radio networks.

Two underwater-specific localization systems with experimental validation are Sufficient Distance Map Estimation (SDME (Mirza & Schurgers, 2008)) and the system proposed by Webster *et al.* (2009). SDME exploits post-facto localization (analogous to post-facto time synchronization of RBS (Elson *et al.*, 2002)) to reduce message counts using an otherwise standard scheme based on all-pairs, broadcast-based, inter-station ranging. They observe localization accuracy of about 1m at ranges of 139m. The system of Webster *et al.* (2009) uses a single moving reference beacon (with GPS-based position) to localize a moving AUV. Their localization scheme is based on acoustic ranging between vehicles with synchronized, high-precision clocks, combined with AUV location estimate from inertial navigation, combined post-facto with an Extended Kalman Filter. In sea trials tracking an AUV at 4000m depths, their scheme estimates position with a standard deviation of about 10–14m.

(*e*) *Sensing and Application Techniques*

While full coverage of sensor technology used in underwater applications is outside the scope of this paper, we briefly summarize some challenges in this section.

Some types of underwater sensors are easy and inexpensive, but many rapidly become difficult and expensive—from a few dollars to thousands or more. Inexpensive sensors include pressure sensing, which can give approximate depth, and photodiodes and thermistors that measure ambient light and temperature (Bokser *et al.*, 2004). More specialized sensors include flourometers that estimate concentrations of chlorophyll (Sukhatme *et al.*, 2006), and devices to measure water CO_2 concentrations or turbidity, and sonar to detect objects underwater. Such specialized sensors can be much more expensive than more basic sensors. Traditional biology and oceanography rely on samples that are taken in the environment and returned to the laboratory for analysis. As traditional underwater research has assumed personnel on site, the cost of sample return is relatively small compared to the cost of getting the scientist to the site. With lower cost sensor networks and AUVs, we expect the costs of sample-return relative to in situ sensing to force revisiting these assumptions.

Algorithms for managing underwater sensing, sensor fusion, and coordinated and adaptive sensing are just beginning to develop. Sonar has been used over more than sixty years for processing single sensors and sensor-array data, and today off-line, pre-mission planning of AUVs has become routine. As the field matures we look forward to work involving on-line, adaptive sampling using communicating AUVs.

(*f*) *Hardware Platforms*

A number of hardware platforms for acoustic communication have been developed over the years, with both commercial, military, and research success. These platforms are essential to support testing and field use.

The Teledyne/Benthos modems are widely used commercial devices. They have been extensively used in SeaWeb (Proakis *et al.*, 2001), with vendor-supported modifications, but their firmware is not accessible to general users, limiting their use for new PHY and MAC research. The Evologics S2C modems (GmbH, 2011) may provide some additional flexibility in that they support the transmission of short packets, which are completely customizable by the users and can be transmitted instantly without any medium access protocol rule (this feature is also supported by the WHOI micro-modem, discussed next). By using such packets, there is some room for implementing and testing protocols, even though the level of reprogrammability of commercial devices remains rather limited in general. The data rates supported by these modems range from a few hundred bps to a few kbps in various bands of the tens of kHz frequency range, over distances up to a few tens of kilometers and with power consumptions of tens of Watts.

Research-specific modems offer more possibilities, although lacking commercial support. The WHOI micro-modem (Freitag *et al.*, 2005) is probably the most widely used device in this category, with a data rate of 80 bps (non-coherent) or about 5 kbps (coherent) with a range of a few km. Other research modems have focused on simple, low cost designs, such as the SNUSE modem at the University of Southern California (USC) and a low-cost hydrophone at the University of California, San Diego, or on reconfigurable, often FPGA-based hardware to support higher speed communications or experimentation, such as in AquaNode at MIT (see (Casari & Zorzi, 2011) for a comparison). A software-defined platform has been proposed in (Torres *et al.*, 2009). Using well-tested tools from wireless radio (such as GNU Radio and TinyOS) and adapting them to work with acoustic devices, this platform provides a powerful means to test protocols in an underwater network and to configure them at runtime.

Several modems (including Teledyne/Benthos, the SNUSE modem, and others) support a low-power receive mode, which could in principle be used to implement wake-up modes for topology control (Harris III *et al.*, 2009). However, integration of this wake-up feature with higher-layer protocols often depends on whether or not the firmware is accessible.

While there is no universal development environment or operating system for underwater research, platforms are generally large enough that traditional embedded systems operating environments are feasible. A number of groups use embedded variants of Linux, for example.

(*g*) *Testbeds*

The breadth of interest in underwater networks has resulted in a great deal of work in the laboratory and simulation, but field experiments remain difficult, and the cost and time of boat rental and offshore deployment are high. Seaweb represents one of the first multi-hop networks, deploying more than a dozen nodes off San Diego in 2000 (Proakis *et al.*, 2001). However, like other contemporary field tests, it was only available to its developers.

More recently at least two groups have explored a testbed that can be shared by multiple projects, or even open for public use. USC has prototyped a small, harbor-based testbed and made it available to other groups (Goodney *et al.*, 2010); WHOI has prototyped a buoy-based, ocean-deployable testbed (Shusta, 2010). Internet-accessible, the USC testbed can be used at any time and for long periods, but it is limited to one location, while the ocean-deployable testbed can be taken to different locations and accessed through surface wireless for temporary deployments. A common goal of these projects is to make experimentation available to a broader group of users. In addition to these steps toward shared testbeds, groups at the University of Connecticut, the National University of Singapore, and the NATO Undersea Research Centre (among others) have deployed medium-to-large scale internal testbeds.

(*h*) *Simulators and Models*

Unlike in RF wireless sensor networks, where experimentation is comparatively accessible and affordable, underwater hardware is expensive (a complete, watertight node can easily cost more than US$1000) and costly to deploy (testing in a public pool can cost US$40/hour due to the mandatory presence of a lifeguard, and deep sea deployments can easily cost tens of thousands of dollars per day), so alternatives are important. Also important is the need for rapid and controlled, reproducible testing over a wide range of conditions. Simulation and modeling is ideal to address both of these problems. Unfortunately, in many instances the accuracy of networking simulators in modeling the physical layer and the propagation effects is poor, limiting the predictive value of such tools.

Many researchers develop custom simulators to address their specific question, and others develop personal extensions to existing tools such as the *network simulator* (ns-2, a popular tool for networking studies (Breslau *et al.*, 2000)). However, distribution and generality of these tools is often minimal, constraining their use to their authors.

Several recent efforts have approached the goal of building underwater simulation tools for the general research community, particularly striving to capture in sufficient detail the key properties of acoustic propagation (Xie *et al.*, 2009; Guerra *et al.*, 2009). For example, WOSS (Guerra *et al.*, 2009) integrates ns-2 with Bellhop (Porter, 2010), a ray-tracing software for acoustic propagation able to predict the sound distribution in a given volume. This approach combines a powerful and widely accepted network simulation tool with an acoustic propagation model that is very accurate in the tens of kHz frequency range, providing results that may represent reasonably realistic scenarios. While not a substitute for experimentation, such simulation frameworks represent a very useful tool for preliminary investigations and for quick exploration of a large design space. A complementary approach also under consideration is to connect a simulator directly to acoustic modems (instead of simulating propagation and PHY), combining simulation and hardware to emulate a complete system.

Several sophisticated modeling tools (including both analytical and computational approaches, e.g., ray tracing) have been developed to study acoustic propagation. However, in most cases the complexity of such models makes them unsuitable for use in the analysis of communication systems and networks, where the time scales involved require lightweight channel/error models and where many lower-level details may have a lesser effect on the overall performance. For this reason, there is currently a strong interest in the development of alternative models, designed to be used in analytical or simulation systems studies. While this is still an open problem, we expect that the recent interests in underwater communication systems and networks will fuel research in this field, making it possible to develop investigation tools that are both accurate and usable.

4. Conclusions and Future Challenges

Applications drive the development of underwater sensing and networking. Inexpensive computing, sensing and communications have enabled terrestrial sensor networking in the past couple of decades, we expect that cheap computing, combined with lower cost advanced acoustic technology, communication and sensing, will enable underwater sensing applications as well.

While research on underwater sensor networks has significantly advanced in recent years, it is clear that a number of challenges still remain to be solved. With the flurry of new approaches to communication, medium access, networking, and applications, effective analysis, integration and testing of these ideas is paramount—the field must develop fundamental insights, as well as understand what stands up in practice. For these reasons, we believe that the development of new theoretical models (both analytical and computational) is very much needed, and that greater use of testbeds and field experiments is essential; such work will support more accurate performance analysis and system characterization, that will feed into the next generation of underwater communications and sensing. In addition, integration and testing of current ideas will stress the seams that are often hidden in more focused laboratory research, such as total system cost, energy requirements, and overall robustness in different conditions.

In addition, we are encouraged by a broadening of the field to consider different options, spanning from high-performance (and cost) to low-cost (but lower performance), and including mobile (human supported or autonomous), deployable, and stationary configurations.

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