A Survey of Practical Issues in Underwater Networks

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Underwater sensor networks are attracting increasing interest from researchers in terrestrial radio-based sensor networks. There are important physical, technological, and economic differences between terrestrial and underwater sensor networks. In this survey, we highlight a number of important practical issues that have not been emphasized in recent surveys of underwater networks, with an intended audience of researchers who are moving from radio-based terrestrial networks into underwater networks.

I. Introduction

Underwater sensor networks are attracting increasing interest from researchers in terrestrial radio-based sensor networks. There are important physical, technological, and economic differences between terrestrial and underwater sensor networks. Previous surveys have provided thorough background material in underwater communications and an introduction to underwater networks. This past work has included detail on the physical characteristics of the channel [1, 2], on underwater acoustic communications [3, 4, 5], and surveys of underwater acoustic networks [6, 7, 8, 9]. In this survey, we highlight a number of important practical issues that are not emphasized in the recent surveys of underwater networks, with references from the ocean engineering literature. Our intended audience is researchers who are moving from radio-based terrestrial networks into underwater networks.

We believe that many, though not all, underwater networks will remain characterized by more expensive equipment, higher mobility, sparser deployments, and different energy regimes when compared with terrestrial sensor networks. We discuss the role of these factors in the different set of challenges that face underwater networks. We identify several of these points in this introduction, and we expand upon them in later sections.

In Section II, we provide a classification scheme for underwater networks. Link-layer range, node density, and geographic coverage of nodes are key factors in determining the type of network deployed.

The key differentiating factor for underwater networks is the use of an acoustic channel. In Section III, we review the basics of such channels. We also mention results from underwater optical and radio communication systems, explain the half-duplex nature of the channel, and discuss the impact of the physical layer on network topology.

Medium access control (MAC) protocols for underwater acoustic sensor networks are still an open problem. In Section IV, we briefly review recent work and mention some directions for future work, including a brief overview of the difficulties with CDMA underwater. For stationary sensor networks, the combination of high propagation delays with energy constraints introduces a new MAC operating regime.

We make an economic argument in Section V that many (though not all) underwater sensor networks will remain *more mobile and more sparse* than terrestrial sensor networks, even as node cost falls. Though sampling is highly non-uniform, the worldwide ocean is vast, and for decades to come, there will be more places to explore than can be covered by dense sensor networks. In mobile underwater networks, there is often contention between communication and navigation signals sharing the same physical channel, leading to new MAC issues. In addition, the combination of mobility and sparsity introduces *long-*

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term fairness as a MAC issue, perhaps leading to prioritized access for nodes that are rarely in contact.

The energy costs in underwater acoustic networks are different from those in terrestrial radio-based networks, as we discuss in Section VI. In acoustic networks *transmit power dominates* compared with receive power. Protocols that optimize energy usage need to be evaluated with this in mind. In addition, in mobile underwater networks with high propulsion energy costs, minimizing network communication energy is not always an important concern. Thus, protocol designers may want to consider alternate metrics, such as reliability, fairness, quality-of-service, or covertness.

II. Underwater Network Operating Regimes

Underwater networks can be characterized by their *spatial coverage* and by the *density of nodes*. These factors have significant implications for the MAC- and network-layer issues that must be addressed at design time. In this section, we create a taxonomy of underwater network operating regimes with the goal of providing context for the discussion later in this paper.

Our taxonomy is illustrated in Figure 1. We characterize the spatial extent of a network by comparing it to the acoustic range of the nodes. If all nodes are in direct contact, we have a single-hop network, with either centralized or distributed control. In networks covering larger areas, communications will require multiple hops to reach destinations. When the geographic coverage is greater than the unpartitioned link-layer coverage of all nodes, routing requires techniques from disruption-tolerant networking (DTN). When even the mobility of nodes does not overlap, no techniques exist to form a network.

There are several additional differences of note between terrestrial radio-based networks and underwater acoustic networks. One is that large populations of nodes in small areas can cause conflicts between throughput and navigation, as we discuss below in Section V.B. A second point is that densely populating even a moderately large geographic area can be prohibitively expensive, as we discuss in Section V.A. This latter point makes DTNs an attractive solution, as we discuss in Section V.C.

In practice, all of the network types shown in Figure 1 are relevant and can exist within an extended network. In other words, clusters of single- or multi-hop networks can be deployed that use DTN routing to exchange information infrequently.

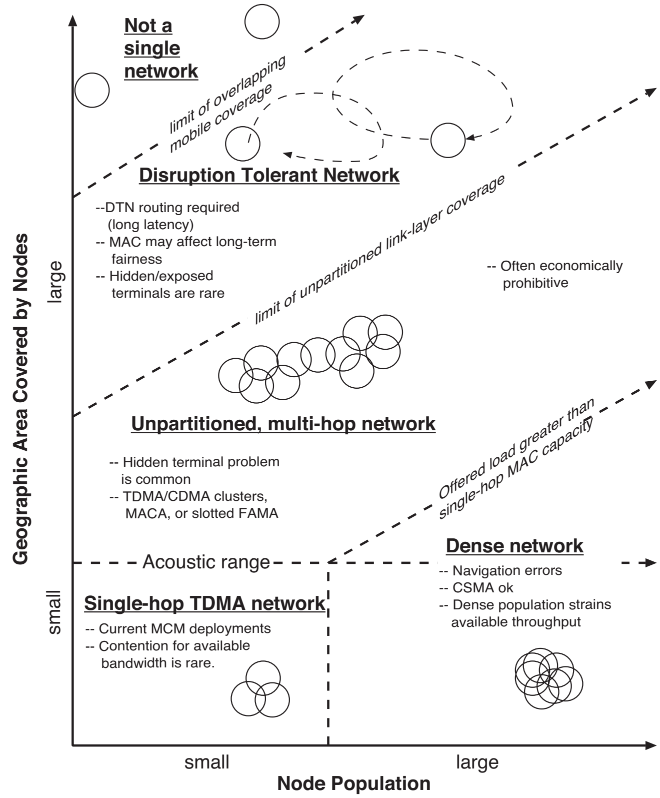

Figure 1: A taxonomy of underwater networking regmines.

In the following sections, we discuss the physical layer and medium access protocols, with particular attention to the differences between underwater networks and terrestrial radio-based networks.

III. Physical Layer

The physical characteristics of the underwater acoustic channel are described well in Catipovic [1] and Preisig [2], and they are summarized here. In addition, we review recent work in long-wave radio and optical underwater networks, and we explain some technological limitations for space-constrained nodes, influencing network topology and leading to a half-duplex channel.

III.A. Physical Channel

Almost all underwater communication uses *acoustics*. Radio waves are extremely strongly attenuated in salt water [10]. Long-wave radio, however, can be used for short distances; for example, about 1kbit/sec at carriers of 1–100kHz for ranges up to 6–20m [11, 10]. Light is strongly scattered and absorbed underwater, though blue-green wavelengths may be used for short-range, high-bandwidth connections in *extremely clear* (often very deep) water. In very clear water, optical modems are expected to achieve data rates up to several Mbits/sec at ranges up to 100m [12]. Underwater optical communication is also being considered for very low-cost, short-range connections of order 1–2m at standard IrDA rates such as 57.6kbits/sec [10, 13].

For longer ranges and more typical water clarity, acoustic communication is the only practical method. A rough performance limit for current acoustic communications is the limit of 40 km·kbps for the range-rate product, though this mostly applies to vertical channels in deep water, and it dramatically overestimates the performance in difficult shallow-water, horizontal channels [3].

The speed of sound underwater is approximately 1500 m/s, which is 2×10^5 times lower than the speed of light. This leads to *large propagation delays* and relatively large motion-induced Doppler effects. Phase and amplitude fluctuations lead to a *high bit-error probability* relative to most radio channels, requiring forward error correction (also called error correction coding). In addition, the acoustic channel has strong attenuation with increasing frequency [14], leading to very *limited bandwidth*.

Multipath interference is common in underwater acoustic networks, causing frequency-selectivity of the channel. This frequency-dependent interference is generally *time-varying* due to surface waves or vehicle motion, causing *fading*. To achieve high bandwidth efficiency, computationally intensive adaptive equalizers are generally required [4], though OFDM-based systems may provide a lower-complexity alternative [15]. While multipath interference is mostly a source of difficulty, recent work using arrays for both transmit and receive (multiple-input, multiple-output, or *MIMO*) takes advantage of the independent channels created by different multipath paths to increase throughput [5].

Over longer paths, frequency-dependent attenuation can suppress certain propagation modes, leading to *shadow zones*, or spatial regions where almost no acoustic signal exists [1]. Also, strong attenuation — on the order of 20dB/m or even higher, persisting for tens of seconds — can occur in near-surface regions with bubble clouds, which are entrained into the water by breaking waves [16]. Both of these effects cause network connectivity dropouts. Relatively small movements can sometimes lead to significantly better channel conditions, which mobile nodes may be able to take advantage of.

Although the underwater acoustic channel is time-varying, *propagation delays are stable and can be estimated*.

III.B. Technological Limitations

Standard acoustic transducers cannot simultaneously transmit and receive. On space-constrained autonomous underwater vehicles (AUVs) and compact stationary nodes, transducers in different frequency bands generally cannot be spatially separated far enough to provide full-duplex connections, since the transmitted signals will saturate the receivers even when the bands are fairly widely separated. Underwater network communications are therefore almost always *half-duplex*. Furthermore, transducer sizes are proportional to wavelength, and due to space constraints, small AUVs are often restricted to using higher center frequencies, generally above 10kHz.

Another technological limitation is that it is easy for small AUVs to transmit at high data rates but often harder for them to receive at high rates. (A high data rate in shallow water would be 5kbits/sec at a range of 2km, for example; a low rate at this range might be as low as 80bits/sec.) The two main reasons for this asymmetry are propulsion noise and some difficulties in mounting receiver arrays on small AUVs [17, 18].

Higher data rates typically use phase-shift keying (PSK) [19], which can be transmitted with a single transducer. Due to the multipath interference, however, equalizing PSK works much better with the spatial diversity provided by an array of receivers [4]. A vertical array is best for equalizing the multipath structure of a typical shallow-water horizontal channel, while a horizontal array can work well for multi-user CDMA systems (see Section IV.B) because users are generally separated azimuthally [17]. Either conformal horizontal arrays or small vertical arrays can be used on AUVs, but performance is somewhat degraded due to propulsion noise and space constraints. On the other hand, frequency-hopped frequency-shift-keying (FH-FSK) [19] provides a lower data rate, which is more robust to AUV propulsion noise and can be received with a single transducer.

The asymmetry in send and receive rates is technological rather than fundamental, but it is a current reality and is one reason that star topologies with base stations are common in existing mobile underwater networks [20]. In these networks, AUVs receive small commands using a low data rate, and they transmit larger sensor data packets at a high data rate back to the base station, generally a gateway buoy with a vertical array to receive PSK and a radio antenna above the water [21]. *Issues at the physical layer can drive topology, affecting routing, medium access, and even applications.*

IV. MAC Protocols

Medium access (MAC) is an unresolved problem in underwater acoustic networks [6, 7, 8, 9]. It has been studied for decades in traditional radio networks [19, 22], and it has received significant attention in radio-based sensor networks as well, recently reviewed by Ali *et al.* [23].

We briefly review recent work in underwater MAC protocols in Section IV.A, discuss some challenges with CDMA in Section IV.B, and outline possible future directions in Section IV.C.

IV.A. Recent Work in Underwater MAC

A range of MAC protocols have been explored in underwater networks.

The Seaweb experiments have been the most extensive and longest-running series of underwater acoustic networking deployments. Seaweb '98 and '99 used FDMA due to modem limitations. With the limited bandwidth and frequency-selectivity of the underwater channel, this was not ideal [24]. More recent Seaweb experiments have used hybrid TDMA-CDMA clusters (see below) with MACA-style [25] RTS/CTS/DATA handshakes. Seaweb includes selective retransmit and provision for channel-adaptive protocol parameters. Seaweb goes well beyond the MAC layer, and it also uses neighbor discovery to determine network routing tables, though using a centralized server architecture [26]. Deployment and configuration takes more than a day, but it can operate for many days, covering regions of over 100 km^2 [24].

Freitag *et al.* [20] describe a single-hop, star-topology AUV network for Mine Countermeasures (MCM) operations. These networks can be rapidly deployed (in about 1 hour) and operate for many hours over regions of about 5 km^2, with many deployments to date. A central gateway buoy provides remote operator control of the AUVs using TDMA with low-rate (e.g., 80bits/sec) commands sent to the AUVs and high-rate (e.g., 5kbits/sec) data returned to the operator via the gateway buoy. The AUV navigation pings (see Section V.B) are also coordinated by the network.

Açar and Adams [27] describe ACMENet, which uses a centralized TDMA protocol with adaptive data rates and power control. They report results from sea trials and provide background discussion on multiple access and MAC protocols for underwater networks.

Smith *et al.* [28] describe an ad hoc network protocol based on CSMA/CA, with prioritized messages and improved access for multi-packet transfers. They report results from a small demonstration. Lapierre *et al.* [29] propose using CSMA/CD, although it is unclear how the collision detection will work in a half-duplex channel. In general, CSMA-based protocols are vulnerable to both hidden and exposed terminal problems [19].

In multi-hop underwater networks, hidden terminals will be common. MACA [25] uses RTS/CTS/DATA packets to reduce the hidden terminal problem, and MACAW [30] adds ACK at the link-layer, which can be helpful in the unreliable underwater channel [6]. FAMA [31] extends the duration of the RTS and CTS packets to prevent collisions with data packets. The efficiency of these protocols are impacted heavily by propagation delays, due to their multi-way handshakes.

A number of adaptations have been proposed to adopt MACA, MACAW, and FAMA for underwater networks. Molins and Stojanovic [32] recently proposed Slotted FAMA, adding time slots to FAMA to limit the impact of propagation delays. Another approach to limit the impact of long RTS/CTS handshake packets is proposed by Peleato and Stojanovic [33], where handshake timing is proportional to the separation of the communicating nodes, and the receivers can tolerate some interference from more distant nodes. As a small part of their review article, Sözer *et al.* [6] described a simulation using MACA with an added WAIT command to reduce collisions and to improve power efficiency. Kebkal *et al.* [34] propose a means to reduce the impact of propagation delay on FAMA- and MACAW-based protocols, with ACK and DATA packets simultaneously in flight. They also suggest an extension to FAMA, using CDMA for the RTS packets, to develop a collision-free FAMA protocol. Related ideas are proposed in more detail in Foo *et al.* [35], with CDMA extensions to MACA and references to the radio-based MAC literature. Foo *et al.* also simulate a MACAW-based underwater network, and they also adapt the AODV reactive ad hoc routing protocol for a sparse underwater network with low mobility.

Another potential approach is using combined TDMA-CDMA clusters, which is used in current Seaweb implementations and described in more detail by Salvá-Garau and Stojanovic [36]. This allows shortening the TDMA slot lengths but increases overhead (cluster assignment) and the potential for interference from a neighboring cluster (using a different code). Doukkali and Nuaymi compare several approaches to underwater MAC, adopting TDMA-CDMA clusters as well [37].

Energy efficiency is also important in underwater networks (see Section VI). In terrestrial sensor networks, energy constraints have led to coordinated-sleeping MAC protocols such as S-MAC [38]. Park and Rodoplu [39] extend these ideas and others, proposing UWAN-MAC, an energy-efficient MAC protocol for delay-tolerant underwater sensor networks; the combination of energy constraints and high propagation delays is a new operating regime for MAC protocols. They also provide references to MAC protocols in underwater networks and terrestrial sensor networks.

IV.B. CDMA

Code-division multiple access (CDMA) [19] is a conflict-free multiple access method which is promising for future underwater networks. Implementing a CDMA-based underwater network is particularly challenging, however, as we discuss briefly below.

Multi-user spread-spectrum methods include frequency-hopped spread spectrum (FHSS, using FSK modulation and lower data rates) and direct-sequence spread spectrum (DSSS, using PSK modulation and higher data rates); the term CDMA usually refers to multi-user DSSS [19, 40]. Each user is assigned a different spreading code with which to transmit. While this reduces each user's throughput compared with the single-user case, users can transmit packets without considering what other users are doing. This would effectively solve many of the MAC problems related to high propagation delay. Furthermore, CDMA has no hard limit on the number of users, and DSSS-based CDMA can perform especially well in multipath environments [41].

Stojanovic and Freitag [42] report very promising CDMA results for four users. An important caveat for this work, however, is that the received power for each of the users was equal. If the received power for all users are not roughly similar, signals from distant users cannot be received successfully [19]. This is the *near-far* problem, and it requires that the transmit power of each user be controlled, as each user's channel varies. This is certainly possible, but *CDMA is more tractable in radio channels than in underwater acoustic channels*. In CDMA-based cell phone networks, closed-loop power control updates are sent 800 times per second, with the feedback propagated at the speed of light. Open-loop power control is also used, where nodes set their transmit power based on the received signal strength from the base station (see Rappaport, Section 10.4, *CDMA Digital Cellular Standard (IS-95)* [19]). Underwater networks have a time-varying, half-duplex channel with a low propagation speed, and so closed-loop transmitter power control is a difficult and open problem. The range of received powers, however, can be moderately wide — up to about 10dB — easing the power control problem somewhat, but with high computational complexity [43].

As an additional note, the power control required with CDMA usually implies a star topology with a single base-station receiver, rather than an arbitrary ad hoc topology. Morns *et al.* [44], however, describe a decentralized configuration using CDMA. Each node in a cluster has its own receive timeslot, during which other nodes can transmit to it using CDMA.

IV.C. Future Directions

Cross-layer optimization and adaptive parameter setting is important given the limited bandwidth and high propagation delays of underwater channels. The control packets in many MAC protocols can provide a means to sample the channel and set network parameters, for example measuring propagation delays to set timeouts, received signal strength to set transmit power, or signal-to-noise ratio to set coding rates. Networks such as Seaweb [26, 24] and ACMENet [27] include provisions for adaptation.

The frequency-dependent attenuation of the underwater channel is different from the radio channel, and it might be used in several different ways. While logistically difficult, a dual-frequency (but still half-duplex) modem [45, 18] could use a lower-frequency transducer for a longer-range, lower-bandwidth link, and a high-frequency transducer for a short-range, high-bandwidth link. This would increase throughput on individual short-range links, and it would also improve spatial reuse, increasing the network's overall throughput. Such a system might also split control and data; long-range control signals could help alleviate hidden-terminal problems.

Some new approaches also try to preserve the broadcast nature of the channel, for *omnicast* within swarms of AUVs, as suggested by Schill *et al.* [46], using TDMA to share control and data for collective behavior of AUVs in an underwater long-wave radio network.

Finally, long propagation delays have been dealt with in satellite and fiber optic networks for many years. In satellite radio networks, several approaches include demand-assignment multiple access (DAMA) [47] and interleaved collision-resolution protocols [48]. Fiber optic networks have used slotted Aloha and coding to deal with propagation delays on the order of 1,000 slots, much higher than in satellite channels [49]. These approaches may provide new ideas for MAC in underwater acoustic networks.

V. Mobility and Sparsity

Terrestrial sensor networks generally assume fairly dense, continuously connected coverage of an area using inexpensive, stationary nodes. In contrast, economics push many underwater networks towards sparse and mobile deployments.

As we discuss in Section V.A, underwater sensor nodes are expensive, and areas of interest in ocean environments are often large, which implies sparse network deployments. Ship-based surveys and sensor deployments are also expensive, and a sparse sensor network with stationary nodes is limited. This has led to the widespread use of mobile AUVs.

In a mobile sensor network, nodes require periodic navigation information. For physical reasons, in underwater networks, navigation and communication signals often share frequency bands. The combined demands on the channel for both navigation and communication places further limits on the density of mobile nodes in a network. We survey network-based approaches to navigation in Section V.B.

The sparsity and mobility of many underwater networks means that disruption-tolerant networks (DTNs) will arise, and mobility patterns strongly influence performance in DTNs. We briefly introduce results from terrestrial DTNs in Sections V.C and V.D, with applicability to underwater networks.

Finally, the sparsity and mobility implies a new operating regime for MAC protocols. As we discuss in Section V.E, in some networks, MAC protocols may prioritize access for AUVs that are within communication range only briefly, to maintain long-term fair access to the channel.

V.A. Economics of Oceanographic Operations

We believe that many, though not all, underwater networks will be sparsely deployed for a long time to come, largely because of the economic costs of individual nodes, but also because of the potentially huge areas to be surveyed. There are several components to the costs of these networks, including fabrication, deployment, and recovery.

Fabrication. An acoustic modem with a rugged pressure housing currently costs[1] roughly $3k. This does not include any underwater sensors, which are often more expensive than the modem itself. Supporting hardware can also drive up costs; e.g., a simple underwater cable connector is often over $100. The high costs are due in part to the rugged construction required to survive storms at sea and deployment at depth[2], but largely due to a small market of demanding users (military, industrial, scientific), and no significant consumer market.

Significantly less expensive sensors, vehicles, and modems (500m-range acoustic and very short-range optical and radio) are being designed and built [8, 50, 51, 13, 10]. These efforts may change the economics for dense underwater sensor networks, as we discuss further below.

Deployment. Oceanographic research ships typically cost from about $5k/day for a coastal boat to $25k/day for a large ocean-going ship [52] (and more when submersibles are used), and their operations are limited in rough weather. Once deployed, stationary or mobile sensor nodes can operate autonomously in almost any weather, a significant advantage. Nodes, however, must be robust and well-engineered, since any repairs will be very expensive.

Recovery. Until nodes are inexpensive (i.e., disposable) and underwater networks have enough bandwidth to enable nodes to fully offload all interesting archived sensor data, recovery will remain a costly operation. Mobile nodes can make the recovery process somewhat easier by moving themselves to a rendezvous point.

Economics and flexibility have led to the use of AUVs as a key element in most underwater network architectures. They operate autonomously once deployed and they have relatively easy deployment and recovery (e.g., about $2k/day for coastal deployment and recovery from a small boat). While AUVs are inexpensive relative to ship time, they are not cheap, starting at over $50k and usually over $250k per vehicle to fabricate and equip. Given the huge size of the ocean, there is a spatial coverage for which deploying an unpartitioned sensor network of AUVs becomes cost-prohibitive, for any given application.

Currently, economics drive underwater sensor networks to be sparse and mobile, as pointed out by several others [8, 9], as well as by us. There are some applications for which a dense, stationary net-

[1] All our estimates are in US dollars.

[2] The pressure increases by an additional atmosphere for every 10m of depth, so even a "shallow"-water (generally 100m) instrument must be able to withstand 10 atmospheres, while "deep"-water instruments (typically 4km) must be rated to at least 400 atmospheres.

work makes economic sense, for example the oil-field monitoring application described by Heidemann *et al.* [8]. The low-cost modems being developed within that project could enable dense underwater sensor networks for other applications, but we believe that sparse and mobile sensor networks will still certainly remain in operation. The ocean covers 70% of the Earth's surface, with an average depth of 4km. This is an immense volume of ocean to survey, even when considering that coverage is generally highly focused and non-uniform. No matter how cheap nodes become, sparse and mobile will remain an important type of underwater sensor network. Ideally, the network protocols will adapt to let mobile nodes move easily between sparse and dense regions of an extended sensor network.

V.B. Contention between Navigation and Data Signals

Autonomous mobile vehicles require navigation information. Underwater, this cannot be supplied by GPS, so, for AUVs, it is often supplied by acoustic transponders, generally in a *long-baseline* (LBL) configuration [53]. In typical high-speed REMUS surveys, each vehicle pings navigation transponders roughly three times per minute to minimize navigation errors. Due to the frequency- and range-dependent attenuation of the channel, high-resolution navigation systems and high-throughput communications systems covering a region of a given size will generally use similar center frequencies, and hence often have interfering signals. In fact, because of this, navigation and communication systems often even share the same transducer [20].

MAC protocols in mobile underwater networks therefore need to be able to share the channel between network communications and navigation signals, with a given navigation quality-of-service. When many vehicles are in an area, each vehicle must reduce the rate at which it pings LBL transponders, which leads to navigation errors.

Several network-based navigation methods have been presented. Freitag *et al.* [53] describe results from a passive navigation system, where a large number of vehicles can passively share navigation signals, analogous to terrestrial GPS, without each vehicle actively pinging a transponder. When vehicles need a more accurate location fix, they can request a slot for an active LBL ping. Elsewhere, Freitag *et al.* [45], have outlined a system for collaborative AUV searches, where high-quality inertial navigation information from a master vehicle is transmitted to companion vehicles, using synchronized hardware clocks and one-way travel-time measurements. Stojanovic *et al.* [54] propose a protocol for collaborative mapping with AUVs. AUVs share their individual maps over the broadcast network, in the process making travel-time measurements and creating a unified map, which can in turn be used for routing. Ouimet *et al.* [55] describe experiments with Seaweb using a broadcast ping packet for AUV localization. Another protocol, ICoN [56], prioritizes navigation and communication packets to ensure that AUVs receive adequate navigation information, yet are still responsive to command packets.

V.C. Disruption-Tolerant Networks

In a sparse and mobile network, DTNs will arise as the link-layer coverage becomes partitioned. When two nodes are in communication range of each other, they have transfer opportunities from the time they discover one another until they are out of acoustic range. Even in radio networks, the amount of data that can be transferred during each opportunity is the most constrained resource; the bandwidths of acoustic modems exacerbate this constraint. (By comparison, the limits on storage at each node are less problematic: storage is generally inexpensive, compact, and energy efficient.) A series of non-contemporaneous meetings between nodes can form a path to a destination. If meetings are frequent and common, then the total throughput that can be delivered by the network can be reasonable for data that remains valuable after long delays. DTNs can also be used to connect geographically remote clusters of nodes.

DTNs have primarily been researched under the assumptions of radio-based terrestrial networks, yet many of the techniques are directly applicable to underwater networking. Most approaches replicate packets *epidemically* during intermittent opportunities for transfer. At the same time, the protocols attempt to limit replication to only the nodes that appear to have some path to the destination. Many approaches to discovering non-contemporaneous paths to destinations use historic information about which nodes meet regularly [57, 58, 59, 60, 61, 62]. Several other techniques are complementary. For example, old packets representing delivered data can be removed from the network using broadcast acknowledgments [59], and network coding [63, 64] can be used to efficiently take advantage of multiple paths.

V.D. Network-Motion Interactions

While the motion of vehicles is primarily determined by their survey patterns, networks can influence the motion in several ways. The most typical is through adaptive and collaborative sampling, where sensor data influences survey patterns [65].

In addition, there is a growing body of work that seeks to improve DTN performance by making use of vehicles with controllable movements. Dunbabin *et al.* [66] have deployed a system on an AUV in a test pool that plans a route to visit stationary underwater nodes in known locations. Zhao *et al.* [67, 68, 69] have several works that investigate DTN routing based on ferries that operate on planned mobility paths; the paths are designed to optimize network performance and known to all other nodes. Burns *et al.* [58, 70, 71] have proposed a method for robotic agents to dynamically adjust movements according to perceived network conditions and according to multiple network objectives, such as maximizing delivery rate and minimizing delivery latency.

Finally, in terms of MAC protocols, AUVs might alter their survey tracklines to alleviate hidden- or exposed-terminal problems and to increase spatial reuse, in a MAC incorporating actual physical "backoffs."

V.E. MAC Fairness in Mobile Networks

With the large propagation delays of the underwater acoustic channel, it is advantageous to transmit packet trains rather than individual packets [72]. Long packet trains can capture the channel, however, and in a mobile DTN, AUVs may move out of range before they are allowed sufficient access to the channel.

This is especially true with AUVs such as the next generation of REMUS vehicles, doubling their speed to 5m/s, and likely reducing their acoustic transmission range to maintain covert communications. With current REMUS vehicles (2.5m/s speed, 2km communication range), a back-of-the-envelope characteristic time to stay within contact is 2km/(2.5m/s)=13 minutes, or about 130 slots for 4-second, 20-kbit data packets with 2-second propagation delays. For the next generation, with a speed of 5m/s and a covert communication range of perhaps 500m, the characteristic time within contact drops to about 2 minutes, or about 20 slots.

In such a network, *long-term average fairness* in accessing the channel becomes an issue. When a previously disconnected AUV re-enters contact briefly, it must be given prioritized access to the channel. One possible mechanism to achieve this is a MAC protocol that adapts its prioritization or backoff probability distribution to account for mobility and disconnectedness, perhaps along with utility-based metrics. We are currently considering this problem, among others.

VI. Energy Efficiency

Energy is limited in both terrestrial and underwater sensor networks. Energy efficiency has been a top priority in MAC protocols for terrestrial sensor networks, with coordinated-sleeping protocols such as S-MAC [38], extended into underwater networks with UWAN-MAC [39]. In addition, a range of approaches to energy-efficient and latency-tolerant underwater network protocols are discussed by Heidemann *et al.* [8].

Despite the constraints on overall system energy, in some mobile underwater acoustic networks, communication energy is not a critical metric for which to optimize. Along similar lines, some terrestrial sensor networks are starting to optimize MAC protocols for a wider range of metrics, such as reliability and quality-of-service [23].

While energy efficiency is likely to improve for both modems and vehicles, current numbers are included below, for comparison purposes.

VI.A. Communication Energy Costs

In most terrestrial radio networks, the power required for transmitting and receiving are approximately the same, with the respective energies being determined by the time spent in the transmit or receive states. In underwater acoustic networks, *transmit power dominates*, and is typically about 100 times more than receive power. A standard acoustic modem currently uses about 0.2W while listening for incoming packets, between 0.2W and 2W for equalizing and decoding packets (depending on the packet's data rate), and typically 50W for transmitting. These figures are representative of sending packets over a range of 2–3km at a 25kHz center frequency, ranging from FH-FSK at 80bits/sec (for poor channel conditions; 0.2W to detect and decode) to PSK at 5kbits/sec (for good channel conditions; 0.2W to detect, 2W during equalization and decoding) [73]. For good channel conditions and shorter ranges, however, the transmit power can be lower, potentially as low as 1W for good conditions and short (500m) ranges [74]. As processors become more energy-efficient, the receive power will continue to drop, while the transmit power will remain roughly constant, as it is determined by channel physics and detector algorithms.

VI.B. AUV Energy Costs

As we discussed in Section V, underwater sensor networks are likely to be more mobile than terrestrial sensor networks, with AUVs being a key network element. For many AUVs, the *propulsion power dominates* network-communication power. Although energy on AUVs is clearly limited, there will be important underwater networks for which network communication energy efficiency is not a primary concern.

As examples, REMUS-class AUVs have missions that are high-speed (1.0m/s-2.9m/s) and short-duration (generally 5-20 hours). Missions can be extended by recharging at sub-sea docking stations. Their "hotel" power load (non-propulsion power: sensors, communication, control computers) is typically about 30W, with a propulsion power consumption ranging from 15W at the optimum speed of 1.5m/s, to 110W at 2.9m/s [75]. In contrast, gliders are low-speed, long-duration vehicles [76]. A glider with electric propulsion has a total power consumption (hotel and propulsion) of about 2W at speeds of 0.2m/s–0.4m/s, for a mission of up to about one month. Thermally powered gliders use variable buoyancy to extract propulsion energy from ocean thermoclines, have extremely long missions (many months or years), and have an extremely low hotel power budget [77]. For high-speed AUV missions, network communication energy can be neglected, whereas it is critical for long-duration glider missions.

Future Energy Directions

Finally, transmit power may be limited for reasons other than battery capacity. One standard networking reason would be to promote spatial reuse. In addition, a concern is the acoustic *impact on marine mammals*, and for military networks, maintaining covert communications is also an important goal.

VII. Conclusions

We have summarized a number of practical issues differentiating underwater acoustic networks from terrestrial radio-based sensor networks. There is no single operating regime for underwater networks, and a wide range will exist. Nevertheless, we believe that many important underwater networks will be more mobile and more sparse than terrestrial sensor networks, with different energy and economic considerations. Underwater network protocols will have to adapt to moving between sparse and dense regions, with different optimization metrics for each regime.

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