Research Challenges and Applications for Underwater Sensor Networking

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Abstract— **This paper explores applications and challenges for *underwater sensor networks*. We highlight potential applications to off-shore oilfields for seismic monitoring, equipment monitoring, and underwater robotics. We identify research directions in short-range acoustic communications, MAC, time synchronization, and localization protocols for high-latency acoustic networks, long-duration network sleeping, and application-level data scheduling. We describe our preliminary design on short-range acoustic communication hardware, and summarize results of high-latency time synchronization.**

I. INTRODUCTION

Sensor networks have the promise of revolutionizing many areas of science, industry, and government. The ability to have small devices physically distributed near the objects being sensed brings new opportunities to observe and act on the world, for example with micro-habitat monitoring [6], [26], structural monitoring [47], and industrial applications [33]. While sensor-net systems are beginning to be fielded in applications today on the ground, *underwater* operations remain quite limited by comparison. Remotely controlled submersibles are often employed, but as large, active and managed devices, their deployment is inherently temporary. Some wide-area data collection efforts have been undertaken, but at quite coarse granularity (hundreds of sensors to cover the globe) [40]. Even when regional approaches are considered, they are often wired and very expensive [12].

The key benefits of terrestrial sensor networks stem from wireless operation, self-configuration, and maximizing the utility of any energy consumed. They emphasize low cost nodes (around US$100), dense deployments (at most a few 100m apart), short-range, multihop communication; by comparison, underwater acoustic communication today are typically expensive (US$10k or more), sparsely deployed (a few nodes, placed kilometers apart), typically communicating directly to a "base-station" over long ranges rather than with each other. We are currently exploring how to extend the benefits of terrestrial sensor networks to *underwater sensor networks with acoustic communications*.

Underwater sensor networks have many potential applications (detailed in Section III). Here we briefly consider seismic imaging of undersea oilfields as a representative application. Today, most seismic imaging tasks for offshore oilfields are carried out by a ship that tows a large array of hydrophones on the surface [25]. The cost of such technology is very high, and the seismic survey can only be carried out rarely, for example, once every 2–3 years. In comparison, sensor network nodes have very low cost, and can be permanently deployed on the sea floor. Such a system enables frequent seismic imaging of reservoir (perhaps every few months), and helps to improve resource recovery and oil productivity.

To realize underwater applications, we can borrow many design principles and tools from ongoing, ground-based sensor-net research. However, some of the challenges are fundamentally different. First, radio is not suitable for underwater usage because of extremely limited propagation (current mote radios transmit 50–100cm). While acoustic telemetry is a promising form of underwater communication, off-the-shelf acoustic modems are not suitable for underwater sensor-nets with hundreds of nodes: their power draws, ranges, and price points are all designed for sparse, long-range, expensive systems rather than small, dense, and cheap sensor-nets. Second, the shift from RF to acoustics changes the physics of communication from the speed of light (3×10^8m/s) to the speed of sound (around 1.5×10^3m/s)—a difference of five orders of magnitude. While propagation delay is negligible for short-range RF, it is a central fact of underwater wireless. This has profound implications on localization and time synchronization. Finally, energy conservation of underwater sensor-nets will be different than on-ground because the sensors will be larger, and because some important applications require large amounts of data, but very infrequently (once per week or less).

We are therefore investigating three areas: *hardware*, acoustic communication with sensor nodes (Section IV); *protocols*, underwater network self-configuration, MAC protocol design, time synchronization, and localization (Section V); and *mostly-off operation*, energy-aware data caching and forwarding (also in Section V). We believe that low-cost, energy conserving acoustic modems are possible, and that our focus on short-range communication can avoid many of the challenges of long-range transfer. Development of multi-access, delay-tolerant protocols are essential to accomplish dense networks. Low-duty cycle operation and integration with the application can cope with limited bandwidth and high latency.

II. SYSTEM ARCHITECTURE

Before describing specific applications, we briefly review the general architecture we envision for an underwater sensor network. Figure 1 shows a diagram of our current tentative design. We anticipate a tiered deployment, where some nodes have greater resources.

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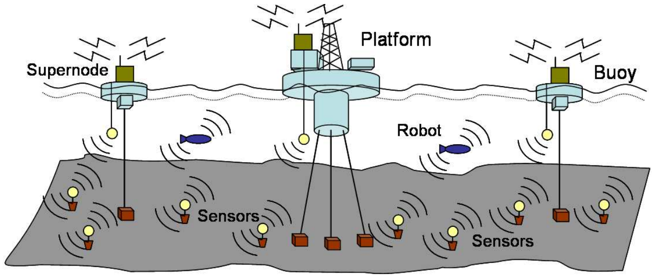

Fig. 1. One possible approach to network deployment.

In Figure 1, we see four different types of nodes in the system. At the lowest layer, the large number of sensor nodes are deployed on the sea floor (shown as small yellow circles). They collect data through attached sensors (*e.g.*, seismic) and communicate with other nodes through short-range acoustic modems. They operate on batteries, and to operate for long periods they spend most of their life asleep. Several deployment strategies of these nodes are possible; here we show them anchored to the sea floor. (They could also be buried for protection.) Tethers ensure that nodes are positioned roughly where expected and allow optimization of placement for good sensor and communications coverage. Node movement is still possible due to anchor drift or disturbance from external effects. We expect nodes to be able to determine their locations through distributed localization algorithms.

At the top layer are one or more control nodes with connections to the Internet. The node shown on the platform in Figure 1 is this kind of node. These control nodes may be positioned on an off-shore platform with power, or they may be on-shore; we expect these nodes to have a large storage capacity to buffer data, and access to ample electrical power. Control nodes will communicate with sensor nodes directly, by connecting to an underwater acoustic modem with wires.

In large networks, a third type of nodes, called *supernodes*, can be deployed. Supernodes have access to high speed networks, and can relay data to the base station very efficiently. We are considering two possible implementations: first involves attaching regular nodes to tethered buoys that are equipped with high-speed radio communications to the base station, as shown in the figure. An alternative implementation would place these nodes on the sea floor and connect them to the base station with fiber optic cables. Supernodes allow a much richer network connectivity, creating multiple data collection points for the underwater acoustic network.

Finally, although robotic submersibles are not the focus of the current work, we see them interacting with our system via acoustic communications. In the figure, dark blue “fishes” represent multiple robots.

CPU capability at a node varies greatly in current sensor networks, from 8-bit embedded processors, such as Berkeley Motes to 32-bit embedded processors about as powerful as typical PDAs, such as Intel Stargates to 32- or 64-bit laptop computers. We see Stargate-class computers as most appropriate for underwater sensor networks for several reasons. Their memory capacities (64MB RAM, 32MB flash storage) and computing power (a 400MHz XScale processor) is sufficient to store and process a significant amount of data temporarily, while their cost is moderate (currently US$600/each). Although Mote-class computers are attractive in cost and energy performance, their very limited memory (4–8kB of RAM and 64–1024MB of flash storage) is a poor match for the requirements of underwater applications that we are considering (see Section III).

In a harsh underwater environment, we must anticipate that some nodes will be lost over time. Possible risks include fishing trawlers, underwater life, or failure of waterproofing. We therefore expect basic deployments to include some redundancy, so that loss of an individual node will not have wider effects. In addition, we expect that we will be able to recover from multiple failures, either with mobile nodes, or with deployment of replacements.

Operating on battery power, sensor nodes must carefully monitor their energy consumption. It is essential that all components of the system operate at as low a duty cycle as possible. In addition, we expect to coordinate with the application to entirely shut off the node for very long periods of time, up to days or months. We also expect to build on techniques for long-duration sleep (for example, [33]). We describe some of our work on energy management in Section V.

Communications between nodes is an important focus of our work, because we see a large gap between our target deployment and currently available commercial, long-range, high-power, point-to-point, acoustic communications. We discuss our approach to low-power, short-range acoustic communications in Section IV. Equally important (and also unaddressed by most current underwater work) are the networking protocols that allow underwater nodes to self-configure and coordinate with each other, such as time synchronization, localization, MAC and routing. We discuss these protocol issues in Section V.

Finally, we have some basic assumptions about the applications that match these design. First, application benefit from local processing and temporary data storage. Storage can be used to buffer data to manage low-speed communications, “time-shifting” data collection from retrieval. In some cases, nodes benefit from pairwise communications and computation. Finally, in most sensing applications, we expect the data to be eventually relayed to the user through the Internet or a dedicated network.

III. APPLICATIONS

We see our approaches as applicable to a number of applications, including seismic monitoring, equipment monitoring and leak detection, and support for swarms underwater robots. We review their different characteristics below.

a) Seismic monitoring: A promising application for underwater sensor networks is seismic monitoring for oil extraction from underwater fields. Frequent seismic monitoring is of importance in oil extraction. Studies of variation in the reservoir over time are called “4-D seismic” and are useful for judging field performance and motivating intervention.

Terrestrial oil fields can be frequently monitored, with fields typically being surveyed annually, or quarterly in some fields, and even daily or "continuously" in some gas storage facilities and permanently instrumented fields. However, monitoring of underwater oil fields is much more challenging, partly because seismic sensors are not currently permanently deployed in underwater fields. Instead, seismic monitoring of underwater fields typically involves a ship with a towed array of hydrophones as sensors and an air cannon as the actuator. Because such a study involves both large capital and operational costs (due to the ship and the crew), it is performed rarely, typically every 2–3 years. As a result, reservoir management approaches suitable for terrestrial fields cannot be easily applied to underwater fields.

Using a sensor network raises a number of research challenges: extraction of data, reliably, from distributed sensor nodes; localization, where each node to determines its location when it is deployed or should it move; distributed clock synchronization clocks for accurate data reporting; energy management approaches to extend sensor network lifetime for a multi-year deployment. We plan to address these challenges through low-power acoustic communication (Section IV) and new protocols for high-latency time synchronization, multiple access, scheduled data access, and mostly-off operation (Section V). To understand the typical requirements of seismic sensing, we carried out a preliminary analysis of the data generated by seismic monitoring. Each sensor collects 3 or 4 channels of seismic data, each having 24 bits/sample at 500Hz. After a seismic event is triggered, we need to capture 8–10s of data. This leads to about 60kB of data per sensor per event. At our expected 5kb/s transfer rate, that implies about 120s/sensor to transfer this data over one hop.

Typical oilfields cover areas of 8km×8km or less, and 4-D seismic requires sensors to approximate a 50–100m grid. (We assume that seismic analysis can accommodate minor, known irregularities in sensor placement.) This implies a fairly large sensor network of several thousand sensors will be required to provide complete coverage. It also implies that a tiered communications network is required, where some supernodes will be connected to users via non-acoustic communications channels. Two possible implementations are buoys with high-speed RF-based communications, or wired connections to some sensor nodes. For a grid deployment we assume one supernode per 25 nodes (a 5x5 segment of the network), suggested all nodes are within two hops of a supernode and time to retrieve all data is about one hour (assuming each supernode can download data in parallel). Of course, one can trade-off the number of supernodes against the time required to retrieve the data. (With supernodes covering areas 4 hops wide, there is only one access point per 81 nodes, but data retrieval time will be much longer due to increased contention at the access point.) We expect to refine our design as we learn more about the problem.

b) Equipment Monitoring and Control: Underwater equipment monitoring is a second example application. Long-term equipment monitoring may be done with pre-installed infrastructure. However, *temporary* monitoring would benefit from low-power, wireless communication. Temporary monitoring is most useful when equipment is first deployed, to confirm successful deployment during initial operation, or when problems are detected. We are not considering node deployment and retrieval at this time, but possibilities include remote-operated or robotic vehicles or divers.

Short-term equipment monitoring shares many requirements of long-term seismic monitoring, including the need for wireless (acoustic) communication, automatic configuration into a multi-hop network, localization (and hence time synchronization), and energy efficient operation. The main difference is a shift from bursty but infrequent sensing in seismic networks, to steady, frequent sensing for equipment monitoring.

Once underwater equipment are connected with acoustic sensor networks, it becomes an easy task to remotely control and operate some equipment. Current remote operation relies on cables connecting to each piece of equipment. It has high cost in deployment and maintenance. In contrast, underwater acoustic networking is able to significantly reduce cost and provide much more flexibility.

c) Flocks of Underwater Robots: A third and very different application is supporting groups of underwater autonomous robots. Applications include coordinating adaptive sensing of chemical leaks or biological phenomena (for example, oil leaks or phytoplankton concentrations), and also equipment monitoring applications as described above.

Communication for coordinated action is essential when operating groups of robots on land. Underwater robots today are typically either fully autonomous but largely unable to communicate and coordinate with each other during operations, or tethered, and therefore able to communicate, but limited in deployment depth and maneuverability.

We expect communications between underwater robots to be low-rate information for telemetry, coordination, and planning. Data rates in our proposed system are not sufficient to support full-motion video and tele-operation, but we do expect to be able to support on-line delivery of commands and the ability to send back still frame images.

IV. HARDWARE FOR UNDERWATER ACOUSTIC COMMUNICATIONS

Acoustic communications is a very promising method of wireless communication underwater. At the hardware level, underwater acoustic communication differs from in-the-air RF in a few key ways. In both systems we transmit a tone or carrier, which carries the data through modulation, such as amplitude, frequency or phase modulation. The primary differences between modulation techniques lies in the complexity of the receiver, the bandwidth required, and the minimum acceptable received signal-to-noise ratio (SNR). SNR is usually expressed as E_b/N_o or *energy per bit over noise spectral density* [30], [46]. As an example, binary frequency shift keying (FSK), requires about 14 dB E_b/N_o for a 1×10^{-6} BER.

The received SNR depends on a few basic factors: the transmitter power, the data rate being sent, the noise level at the receiver, and the signal attenuation between the transmitter and receiver. We review each of these constraints next.

d) Transmit Power: There is no fundamental limit to transmitter power, but it can have a major effect on the energy budget for the system. For energy efficiency and to minimize interference with neighboring transmitters we wish to use the smallest possible transmitter power.

e) Data Rate: This is a tradeoff between available power and channel bandwidth. Because acoustic communications are possible only over fairly limited bandwidths, we expect a fairly low data rate by comparison to most radios. We see a rate of currently 5kb/s and perhaps up to 20kb/s. In application such as robotic control, the ability to communicate *at all* (even at a low rate) is much more important than the ability to send large amounts of data quickly.

f) Noise Level: Noise levels in the ocean have a critical effect on sonar performance, and have been studied extensively. Burdic [4] and Urick [44] are two standard references. We are interested in the frequency range between 200 Hz and 50 kHz (the *midfrequency band*). In this frequency range the dominant noise source is wind acting on the sea surface. Knudsen [21] has shown a correlation between ambient noise and wind force or sea state. Ambient noise increases about 5dB as the wind strength doubles. Peak wind noise occurs around 500 Hz, and then decreases about -6dB per octave. At a frequency of 10,000 Hz the ambient noise spectral density is expected to range between 28 dB/Hz and 50 dB/Hz relative to 1 microPascal. This suggests the need for wide range control of transmitter power.

g) Signal Attenuation: Attenuation is due to a variety of factors. Both radio waves and acoustic waves experience $1/R^2$ attenuation due to spherical spreading. There are also absorptive losses caused by the transmission media. Unlike in-the-air RF, absorptive losses in underwater acoustics are significant, and very dependent on frequency. At 12.5kHz absorption it is 1dB/km or less. At 70kHz it can exceed 20dB/km. This places a practical upper limit on our carrier frequency at about 100kHz.

There are additional loss effects, mostly associated with scattering, refraction and reflections (see [41] for a good overview). A major difference between RF and acoustic propagation is the velocity of propagation. Radio waves travel at the speed of light. The speed of sound in water is around 1500 m/s, and it varies significantly with temperature, density and salinity, causing acoustic waves to travel on curved paths. This can create silent zones where the transmitter is inaudible. There are also losses caused by multipath reflections from the surface, obstacles, the bottom, and temperature variations in the water and scattering from reflections off a potentially rough ocean surface.

h) Proposed Acoustic Communications Design: Many of these forms of loss are unique to acoustic communications at *longer* distances. In particular, multipath reflections, temperature variation, and surface scattering are all exaggerated by distance. Inspired by the benefits of short range RF communication in sensor networks, we seek to exploit *short-range underwater acoustics* where our only significant losses are spreading and absorption. We are developing a multi-hop acoustic network targeting communication distances of 50-500 meters. Using a simple FSK signaling scheme we anticipate sending 5kb/s over a range of 500m using a 30 mW transmitter output. The primary limitation is set by spreading loss and the background noise of the ocean.

Low-power listening is an important technique in RF-based sensor networks [37], [19], [13], [28]. We are also developing a very low power *wakeup receiver* to better support low-power listening. This receiver is not intended for data exchange, but only to detect possible transmission by checking acoustic energy in the channel. When transmission is detected, it wakes up the data receiver/processor to communicate. Our current hardware design using a dual gate FET configured as a cascode amplifier, with a passive filter and detector. The filter has a Q of 30, and a center frequency of 18kHz. The circuit consumes 100μA at 5 volts (500μW).

V. PROTOCOLS FOR HIGH-LATENCY NETWORKS

Acoustic communication puts new constraints on *networks* of underwater sensor nodes for several reasons. First, the large propagation delay may break or significantly degrade the performance of many current protocols. For example, propagation delay for two nodes at 100m distance is about 67ms. Second, the bandwidth of an acoustic channel is much lower than that of a radio. Efficient bandwidth utilization becomes an important issue. Finally, unlike terrestrial networks, underwater sensor networks cannot take advantage of rich existing infrastructure such as GPS. We next examine several research directions at the network level.

A. Latency-Tolerant MAC Protocols

MAC protocols suitable for sensor networks can be broadly classified into two categories [50]: scheduled protocols, *e.g.*, TDMA, and contention protocols, *e.g.*, CSMA. TDMA has good energy efficiency, but requires strict time synchronization and is not flexible to changes in the number of nodes. Contention-based protocols have good scalability and adaptivity to changes in the number of nodes. Their energy efficiency can be improved by enabling low-duty-cycle operations on nodes, such as S-MAC [51], [52], STEM [38], [37], low-power listening [19].

Currently, contention-based protocols with low duty cycles are widely studied by the sensor network community and results are promising. However, the large propagation delay in acoustic communications is particularly harmful to contention-based protocols for several reasons. First, it may take very long time for a node to detect concurrent transmission with carrier sense. For example, suppose two nodes at a distance of 100m. If they try to send at about the same time, *e.g.*, triggered by the same sensing events, they need to listen for at least 67ms to avoid collisions. Furthermore, if they exchange RTS and CTS, the overall propagation delay is tripled.

Figure 2 shows the periodic listen and sleep schedule of a sensor node running S-MAC in low duty cycles. The top part (a) shows the length of the listen window in current implementation in TinyOS, which is about 120ms for listening SYNC, RTS and CTS packets. The bottom part (b) shows a naive extension to S-MAC where we modify the listening window to accommodate the propagation delays for each packet, now about 320ms. With this naive approach, a propagation delay will significantly increase the actual duty cycles of nodes, increase latency and decrease throughput, especially in multi-hop networks.

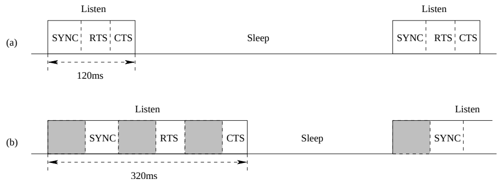

Fig. 2. Modified S-MAC schedules to accommodate large propagation delay. (a) shows the listen window length currently implemented in TinyOS. (b) shows increased listen window to accommodate propagation delay of each packet.

Clearly a major focus of MAC research will be to redesign media access protocols from the ground up to consider large propagation delays, rather than to simply adapt existing MAC protocols. First, we will examine the details of how the propagation delay affects energy efficiency, latency and throughput on existing protocols. Then, based on our understanding of the problem, we will develop new approaches to better accommodate the large propagation given the constraints in underwater sensor networks. Possible directions include designing new sleep and wake-up schemes, reducing control packet exchange, and combining contention-based transmissions with scheduled transmissions.

B. *Time Synchronization*

Without GPS, distributed time synchronization provides fundamental support for many protocols and applications. Several algorithms have been developed for radio-based sensor networks, such as RBS [14] and TPSN [17], achieving the accuracy of tens of microseconds [14], [17]. However, they assume nearly instantaneous wireless communication between sensor nodes, which is valid enough for radio networks (*e.g.*, 0.33μs for nodes over 100m). In underwater acoustic networks, the large propagation delay becomes a dominant source of error in these protocols. Hence we have designed a new protocol, Time Synchronization for High Latency (TSHL), that well manages the errors induced by the large propagation latency [43].

TSHL splits time synchronization into two phases. In the first phase, nodes model their clock skew to a centralized timebase, after which they become *skew synchronized*. In the second phase they swap *skew compensated* synchronization messages to determine their exact offset. The first phase is impervious to the propagation latency, while the second phase explicitly handles propagation delay induced errors. This results in fast relative synchronization (end of phase 1), and also allows us to do *post-facto* synchronization. Both of these properties are highly desirable in our intended applications.

We have evaluated TSHL in simulation to consider the effect of distances (and hence propagation latency), tolerance to clock skew, and design parameters of TSHL such as number of beacon messages used to estimate skew. At all distances, clock synchronization accuracy of TSHL is much better than RBS (by a factor of two or more), since RBS does not consider propagation latency at all. Figure 3 compares TSHL against TPSN, a protocol that considers propagation delay but not clock skew. At short distances of less than 50m, synchronization accuracy of TSHL and TPSN are comparable, since for these distances clock skew during synchronization is minimal. At longer distances the clock skew causes increasing errors in TPSN, up to twice the error in TSHL at 500m. These values are immediately after the algorithm runs. Errors in clock estimation are magnified after synchronization, so TSHL is even better when synchronization messages are done rarely to conserve energy.

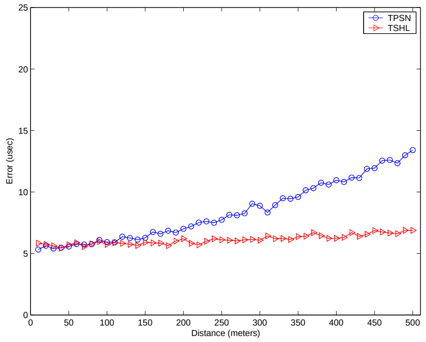

Fig. 3. Comparison of clock synchronization error between TSHL and a TPSN-like protocol, immediately after a message exchange as distance between nodes increases.

We are in the process of implementing TSHL. Before our short-range acoustic modems are ready, we have used in-the-air acoustic communication with the Cricket platform [29] as a substitute for underwater communication.

C. *Localization*

Localization is the process for each sensor node to locate its positions in the network. Localization algorithms developed for terrestrial sensor networks are either based on the signal strength [2], [3] or the time-of-arrival (TOA) [36], [18]. Signal strength only gives proximity information but not accurate locations TOA-based algorithms provide fine-grained location information, which is required by our seismic imaging application.

TOA-based algorithms estimate distances between nodes by measuring the propagation time of a signal. The basic principle is the same as radar or sonar, but is carried out in a distributed way among peering nodes. TOA measurement requires precise time synchronization between a sender and a receiver, and we will rely on our time synchronization work described in Section V-B. Once the measurement is done among neighboring nodes, multilateration algorithms can be applied for each node to calculate its relative position to some reference nodes. If supernodes are placed on buoys, they are able to use GPS to obtain precise global locations, which can then be used as references to all underwater nodes. If supernodes are connected via wired networks, then we assume their locations can be surveyed when they are deployed and so they can again offer points of location reference.

While similar localization systems have been developed for terrestrial sensor networks (*e.g.*, [27]), the accuracy of such systems need to be evaluated in the underwater environment.

Unlike radio propagation, the speed of sound changes in the environment, based on temperature, pressure and salinity [9]. The propagation path may even be curved due to uneven temperature distribution. Moreover, node movement due to waves needs to be considered. All these factors affect localization accuracy and need to be studied.

D. Network Re-Configuration after Long Duration Sleeping

Undersea seismic monitoring of oil fields is an "all or nothing" application—periodically a seismic experiment will be triggered and all nodes must collect high-resolution seismic data for a few minutes, then a few months may go by with no activity. It would be extremely wasteful to keep the network fully operational for months at a time to support occasional measurements. Instead, we expect to put the whole network to sleep for the entire inactive period, and let it restart quickly when needed. Similar approaches are also appropriate for long-term equipment monitoring, where nodes only need to check equipment status once a day or a week [33]. This type of network configuration is in effect "sensor network suspend and resume". It is different than low-duty-cycle MAC protocols, which provides the illusion that the network is always up.

The major research issue is how to efficiently re-configure the network after a long sleep period. Nodes will agree on the same "resume" moment before entering the periodical long sleep. However, due to clock drift, they will wake up at different moments. When the drift rate is 50 parts per million (ppm), the maximum clock difference after 30 days is about 130 seconds. A naive approach is to let each node wait in listening mode for twice the maximum clock dift, counting two possible directions of drifts. Thus, it requires at least four minutes to reboot the whole network!

There are two challenges in network re-configuration. First, the re-configuration phase after a long sleep should be as short as possible to restart the network quickly. Sensor nodes also need to stay energy efficient during these periods. Another challenge is to configure the network such that other protocols like MAC can resume quickly when the network restarts.

We propose two approaches. The first one is *low power listening with flooding*. Right after nodes wake up asynchronously, they set up a timer that is twice the length of the maximum clock drift and perform low-power listening (sampling the channel for activity [13], [19]). When the first node times out, all nodes should have restarted. It sends a "Network Up" message immediately and the whole network starts flooding the message. Upon receiving the propagated message, nodes realize the network has resumed and data transmissions can begin immediately. This approach restarts network quickly by flooding and nodes stays energy efficient with low power listening.

Our second protocol, *requests with suppression*, tries to avoid the flooding overhead. The first node that wakes up sets the network resume time. When a new node wakes up, it sends a request packet to get the time from any already active nodes. To save energy, both requests and replies are suppressed if possible using random delays—nodes listen for concurrent requests or replies and use them as their own.

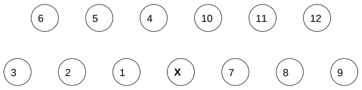

Fig. 4. Extracting data from an underwater sensor grid.

The cost of reconfiguring a network must include the cost of brining up a fully functional MAC protocol, including adopting a consistent schedule [23]. Our protocols support both random access and scheduled MAC protocols. Our preliminary analysis suggests that we can achieve significant energy savings for both classes of MAC protocol compared to simply leaving nodes on idle listening during network re-configuration. We are currently at the stage of implementing both protocols in TinyOS to verify their performance.

E. Application-Level Data Scheduling

Besides energy constraints, acoustic networks also have very limited communications bandwidth. Today's off-the-shelf acoustic modems typically have the bandwidth between 5–20Kb/s. With applications like seismic imaging, all nodes will collect and try to send large amount of data that can easily overwhelm the network capacity. The research issue here is how to coordinate node's transmissions in an energy-efficient way that can best utilize the channel.

Current MAC protocols operating at 1–10% duty cycle provide the abstraction of a network that is always up by transparently delaying packets until the next awake period. This approach is not efficient for nodes to transmit large data at about the same time, as excessive MAC-level contention wastes bandwidth and energy. Instead we will explore explicit *application-level data caching and forwarding*. Building on the work of Delay Tolerant Networking [15], we plan to package sensor network readings and pass them from sensor node to sensor node.

While DTN outlines a generic architecture for store-and-forward data delivery, our seismic imaging application raises important application-level scheduling issues. For example, assume each sensor in Figure 4 must send 2.4MB of seismic data to the extraction node (indicated with an "X"), and that each node can talk only to its immediate neighbors. Assuming an acoustic radio at 20kb/s, raw transfer time for one node is 16 minutes. Unscheduled transmission of all data would have all nodes competing to send and awake for at least 4 hours, and in practice much longer due to channel contention at node X. If instead we schedule nodes to transfer data in the order given by node-id, then in the worst case, the nodes nearest X are each up for only 48 minutes (a savings of 77%), and edge nodes for only 16 minutes. Scheduling transmissions at the application level avoids excessive MAC-level contentions and can better utilize the channel and save energy.

VI. RELATED WORK

We build our research directions on related work from two major communities: oceanographic researchers and the wireless sensor network community.

A. *Oceanographic research*

Oceanographic researchers have developed underwater sensing and communication systems. An example is the Ocean Seismic Network program [40]. It developed seismic observatories in the deep ocean, as part of the Global Seismic Network (GSN). GSN has 128 observatories "uniformly" distributed on continents, islands or in the ocean, with a separation distance of 2000km. Its goal is to monitor a huge area on earth. In contrast, our sensor network covers a much smaller area, and nodes are densely deployed in an ad hoc fashion.

Underwater acoustic communication is another related area. The basic communication principles have been examined with acoustic channels in [31], [5], [41], [42]. Their major focus is the transmission range, bandwidth utilization and reliability with multi-path propagations. There are also experimental and commercial off-the-shelf acoustic modems available today, such as [34], [1], [24]. However, they are designed for long range communications (1–90km), and have weights of over 4kg. In our hardware design, we focus on short range, low-power modules in a small package. This capability is an enabling factor for long-lived sensor networks.

The NEPTUNE project [12] built an underwater sensor network with all nodes being connected by fiber-optic submarine cables. Follow-on work to the NEPTUNE network extended the wired network with some battery-powered nodes with acoustic communications [16]. In [16], the authors discussed the efficiency and reliability of modulations, and also briefly compared traditional MAC protocols. The major difference of our sensor network model is that there will be no expensive cables laying on the sea floor. Most nodes will be cheap, small and battery-powered for easy deployment. Our work is focused on network self-organization, longevity, and multi-hop communications.

B. *Wireless sensor networks*

So far, most work in the sensor network community has focused on terrestrial sensor networks. Virtually all *platforms* use radio communications. The UC Berkeley motes [20], [11] are based on 8-bit microcontrollers and short-range radios. 32-bit platforms are normally embedded PCs, such as PC/104s and Stargates [11]. Although the radio propagation in water is very bad, the motes are still used by researchers in marine microorganism monitoring applications [53]. We plan to extend sensor network platforms with a low-power, short-range acoustic communication device, so that large-scale underwater experiments and applications become possible.

There are several *networking protocols and algorithms* directly related to our proposed research. In fine-grained time synchronization algorithms, RBS synchronizes different receivers to a common reference broadcast signal [14], and TPSN is based on sender and receiver pairs [17]. As discussed in Section V-B, both of them do not handle the errors caused by the large propagation delay. Fine-grained localization algorithms [36], [18] measure the TOA, and relies on fine-grained time synchronization. Their performances are not evaluated with underwater acoustic communications.

Current research in the MAC layer is mainly on contention-based protocols, although TDMA protocols have been studied [32]. The major focus is energy efficiency, and several low-duty-cycle schemes have been proposed, such as S-MAC [51], [52], T-MAC [45], WiseMAC [13], and B-MAC [28]. New approaches need to be developed to accommodate large propagation delays.

Prior work on *low-duty-cycle operation* aims to provide the illusion of constant network access with the MAC-level sleep/wakeup. An application-level approach exploits dense deployment by putting redundant nodes into sleep [49], [8], [7]. Now we are dealing with much longer sleep time with no application activities during sleeping. None of the above protocols are optimized for this type of applications. We must have new protocols to completely shut down and quickly restart the network.

Another area of related work is the Delay Tolerant Networking [15]. It outlines a generic architecture for store-and-forward data delivery. However, we need to further investigate important application-level scheduling issues in the underwater environment.

C. *Underwater networks*

There is some prior work in underwater acoustic networking. In [39], the authors reviewed MAC, routing, and energy consumption for ad hoc networks. In [48], the authors studied the latency effects in acoustic communications and proposed a topology discovery algorithm. In [35], the authors proposed a clustering protocol with combined TDMA and CDMA for a group of autonomous underwater vehicles. Codiga et al. have demonstrated small-scale networks off Long Island [10]. This research assumes an ad hoc networking model with small to moderate number of nodes. In contrast, our sensor network model consists of hundreds to thousands of nodes, and our application has different requirements.

More recently, concurrent with our work, Kong et al. have outlined a research direction in underwater ad hoc networking [22], emphasizing simulation of localization, security, and location-based routing in military applications. Our work instead focuses on prototype hardware and adds time synchronization and other applications.

VII. CONCLUSIONS

This paper has summarized our ongoing research in underwater sensor networks, including potential applications and research challenges.

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