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A Paper on Low Propagation Delay Routing Protocol for Acoustic Underwater SENSORS Network

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***Abstract*—Underwater sensor nodes will always have applications in underwater data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications. Moreover, unmanned or autonomous underwater vehicles (UUVs, AUVs), equipped with sensors, will enable the exploration of natural under-sea resources and gathering of scientific data in collaborative monitoring missions. Underwater acoustic networking is the enabling technology for these applications. Underwater networks consist of a variable number of sensors and vehicles that are deployed to perform collaborative monitoring tasks over a given area.**

In this paper, several fundamental protocols used for underwater communication are compared and a new protocol better than the older ones is proposed. Different architectures for two-dimensional and three-dimensional underwater sensor networks are discussed, and characteristics of proposed protocol are discussed. The main challenges for the development of efficient networking solutions posed by the underwater environment are detailed and a cross-layer approach to the integration of all communication functionalities is suggested. Furthermore, open research issues are discussed and possible solution approaches are outlined.

***Index Terms*—Underwater sensor network, Routing, Flooding Multipath, Cluster, AUV (autonomous underwater vehicle).**

I. INTRODUCTION

UWASN is rapidly increasing interest from scientist and business group, because there are large resources in the sea. As we know, human cannot go for underwater environment exploration and deployments cost in underwater based networks is much higher than terrestrial based networks.

Typically communication in UWASN spends about ten thousand dollar. Large surface and deep height result in underwater equipment are sparsely deployed. In the past three decade, most applications of UWASN are usually applied for undersea exploration. The UWASN is used to extracting oil or detecting reservoirs from underwater, navigation, tactical surveillance. It is a long-term exploration and typically have spent many years to discover resources. For the application of the pollution monitoring, the UWASN also used for disaster prevention, such as tsunami warning or seaquakes investigation. Besides, the military reconnaissance is also an important application for UWASN. The Navy uses UWASN to perform anti- submarine mission because submarines and mines always cause serious damages. In the wireless sensor network (WSN), sensor nodes are only restricted to work in low power consumption for power saving. However, the UWASN has more restrictions because of intrinsic properties. The first is the propagation delay. The propagation speed in water (1.5×103 m/s) is lower than radio propagation speed (3×108 m/s). Second the power consumption for underwater sensor. Underwater sensor nodes mainly use battery power. It is a difficult task to change the battery for senor node in water[8].

To realize underwater applications, we can borrow many design principles and tools from ongoing, ground-based senso rnet 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_108m/s) to the speed of sound (around 1:5_103m/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, number of rounds a node takes before dying, number of data packets it passes per 100 rounds, 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.

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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.

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.

However a number of problems confront us in achieving this goal. Some such as power efficiency, deployment and repair are common to wireless sensor network deployments on land, though more difficult in the underwater environment. Other issues render the problem radically different .A key issue is communications | current terrestrial wireless sensor network applications to date have used radio. At frequencies that are practical with low-cost radio chips and compact antennas, radio waves are attenuated so strongly in salt water that radio communications is impractical.

The calculations are simplistic and ignore protocol and routing overhead. Nevertheless we can see that the energy consumption by the underwater network is over four orders of magnitude lower with the use of AUV data mulling. If we further consider the cost of an optical communications board at $50/node and the cost of the acoustic modem at $3000/node, we argue that the most efficient way for collecting data from an underwater sensor network is using a system capable of optical communications with static and mobile nodes, such as the one described in this paper. The mobile nodes will require power to navigate the sensor network but they are easily rechargeable. The mobile node will maximize the lifetime and storage utilization for a fixed configuration underwater sensor network. We have created an asymmetry in the communications power required, enabling very low power operations on the nodes that are difficult to access and have fixed energy reserves. By contrast, the AUV which is mobile and can be recharged at the end of each mission, takes on the energy expensive role.

The energy per bit for acoustic modems is more difficult to obtain. The WHOI modem [2] has a data rate of 220 bits/sec over 5000 m at 10W in transmission mode, or 20mJ/bit. The Aqua communication modem has a data rate of 480bit/s over 200m at 0.45W, or 4.5mJ/bit. Heidemann [11] anticipates 5kbit/s over 500m at 30mW transmit power but does not provide the total power required or show experimental results. For this analysis we will assume 480bit/s at 4.5mJ/bit with a range of 200m. Thus the 6.86 Mbytes of data would require 1.3 days to transmit and the total energy consumed will be 247kJ. Because the modems have only 200m range the data transfer will require multiple hops. If the average path length in the network is 5km this will involve 25 hops, so the total energy consumed will be 6.2MJ. In order to avoid collisions in the shared acoustic medium a sophisticated MAC strategy would be required. This strategy may also require a clock synchronization protocol.

Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances through conductive salty water only at extra low frequencies (30 − 300Hz), which require large antennae and high transmission power. For example, the Berkeley MICA2 Motes, a popular experimental platform in the sensor networking community, have been reported to reach an underwater transmission range of 120 cm at 433MHz in experiments performed at the University of Southern California. Optical waves do not suffer from such high attenuation but are affected by scattering. Furthermore, transmitting optical signals requires high precision in pointing the narrow laser beams. Thus, communication in underwater networks are typically based on acoustic wireless communications.

The traditional approach for **ocean-bottom or ocean-column** monitoring is to deploy underwater sensors that record data during the monitoring mission, and then recover the instruments [19] [20].

The key benefits of terrestrial sensor networks stem from wireless operation, self-configuration, and maximizing the utility of any energy consumed. We are currently exploring how to extend these benefits to *underwater sensor networks with acoustic communications*. It is instructive to compare current terrestrial sensor network practices to current underwater approaches. Terrestrial networks emphasize low cost nodes (around US$100), dense deployments (at most a few 100m apart), multihop communication, short-range communication; by comparison, typical underwater wireless communication today are typically expensive (US$10k or more), sparsely deployed (a few nodes, placed kilo meters apart), typically communicating directly to a .base-station. Over long ranges rather than with each other. We seek to reverse each of these design points, developing underwater sensor nodes that can be inexpensive, densely deployed, and communicating peer-to-peer.

Underwater sensor networks have many potential applications, including seismic monitoring, equipment monitoring and leak detection, and support for swarms underwater robots (explored in more detail in Section 3). Here we briefly consider seismic imaging of undersea oil fields as a representative application. One major reason to choose this application is that underwater sensor network is able to provide significant economic benefits over traditional technology. Today, most seismic imaging tasks for offshore oil fields are carried out by a ship that tows a large array of hydrophones on the surface [30]. 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 (e.g. once every 3 months), and helps to improve resource recovery and oil productivity.

To realize these applications, an underwater sensor net work must provide many of the tools that have been developed for terrestrial sensor networks: wireless communication, low-power hardware, energy conserving network protocols, time synchronization and localization, and programming abstractions. We can borrow many of these tools from ongoing, ground-based sensornet research. However, some of the challenges are fundamentally different. First, radio is not generally suitable for underwater usage because of extremely limited propagation (current mote radios transmit 50.100cm). While acoustic telemetry promises an alternative method of underwater wireless communication, off-theshelf acoustic modems are not suitable for large-scale underwater sensor-nets: 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_108m/s) to the speed of sound (around 1:5_103m/s).a difference of 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 ranging 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 4); *protocols*, underwater-network network self-configuration, MAC protocol design, time synchronization, and ranging (Section 5); and *mostly-off operation*, data caching and forwarding and energy-aware system design and ultra-low duty cycle operation (also in Section 5).

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 and involvement of the application can cope with limited bandwidth and high latency.

Solving these constraints in the abstract is an underspecified problem; many solutions are possible, only some off which are likely useful. We begin by reviewing our over all architecture (Section 2) and the constraints placed on our work by several applications (Section 3).

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 multiyear 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 super rnodels 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 super rnodel per 25 nodes (a 5x5 segment of the network), suggested all nodes are within two hops of a super rnodels and time to retrieve all data is about one hour (assuming each super rnodels can download data in parallel). Of course, one can trade-off the number of super rnodels against the time required to retrieve the data. (With super rnodels 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 below-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.

Environmental-monitoring UW-ASNs can per-form pollution monitoring (chemical, biological and nuclear). For example, it may be possible to detail the chemical slurry of antibiotics, estrogen-type hormones and insecticides to monitor streams, rivers, lakes and ocean bays (water quality in situ analysis) [51]. Monitoring of ocean currents and winds, improved weather forecast, detecting climate change, under-standing and predicting the effect of human activities on marine ecosystems, biological monitoring such as tracking of fishes or micro-organisms, are other possible applications. For example, in [52], the design and construction of a simple underwater sensor network is described to detect extreme temperature gradients (thermo-clines), which are considered to be a breeding ground for certain marine micro-organisms.

- Undersea explorations. Underwater sensor net-works can help detecting underwater oilfields or reservoirs, determine routes for laying under-sea cables, and assist in exploration for valuable minerals.

- Disaster prevention. Sensor networks that measure seismic activity from remote locations can provide tsunami warnings to coastal areas [42], or study the effects of submarine earthquakes (seaquakes).

- Assisted navigation. Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling.

- Distributed tactical surveillance. AUVs and fixed underwater sensors can collaboratively monitor areas for surveillance, reconnaissance, targeting and intrusion detection systems. For example, in [15], a 3D underwater sensor net-work is designed for a tactical surveillance system that is able to detect and classify submarines, small delivery vehicles (SDVs) and divers based on the sensed data from mechanical, radiation, magnetic and acoustic micro-sensors. With respect to traditional radar/sonar systems, underwater sensor networks can reach a higher accuracy, and enable detection and classification of low signature targets by also combining measures from different types of sensors.

- Mine reconnaissance. The simultaneous operation of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine-like objects.

Underwater networking is a rather unexplored area although underwater communications have been experimented since World War II, when, in 1945, an underwater telephone was developed in the United States to communicate with submarines [39]. Acoustic communications are the typical physical layer technology in underwater networks. In fact, radio waves propagate at long distances through conductive sea water only at extra low fre-quencies (30–300 Hz), which require large antennae and high transmission power. For example, the Berkeley Mica 2 Motes, the most popular experimental platform in the sensor networking community, have been reported to have a trans-mission range of 120 cm in underwater at 433 MHz by experiments performed at the Robotic Embedded Systems Laboratory (RESL) at the University of Southern California. Optical waves do not suffer from such high attenuation but are affected by scattering. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams. Thus, links in underwater networks are based on acoustic wire-less communications [45].

The traditional approach for ocean-bottom or ocean-column monitoring is to deploy underwater sensors that record data during the monitoring mission, and then recover the instruments [37]. This approach has the following disadvantages:

- No real-time monitoring. The recorded data can-not be accessed until the instruments are recovered, which may happen several months after the beginning of the monitoring mission. This is critical especially in surveillance or in environmental monitoring applications such as seismic monitoring.

- No on-line system reconfiguration. Interaction between onshore control systems and the monitoring instruments is not possible. This impedes any adaptive tuning of the instruments, nor is it possible to reconfigure the system after particular events occur.
- No failure detection. If failures or mis-configurations occur, it may not be possible to detect them before the instruments are recovered. This can easily lead to the complete failure of a monitoring mission.
- Limited storage capacity. The amount of data that can be recorded during the monitoring mission by every sensor is limited by the capacity of the onboard storage devices (memories, hard disks).

Therefore, there is a need to deploy underwater networks that will enable real-time monitoring of selected ocean areas, remote configuration and interaction with onshore human operators. This can be obtained by connecting underwater instruments by means of wireless links based on acoustic communication.

Many researchers are currently engaged in developing networking solutions for terrestrial wireless ad hoc and sensor networks. Although there exist many recently developed network protocols for wireless sensor networks, the unique characteristics of the underwater acoustic communication channel, such as limited bandwidth capacity and variable delays [38], require very efficient and reliable new data communication protocols.

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 *Eb=No* or *energy per bit over noise spectral density* [30], [46].
As an example, binary frequency shift keying (FSK), requires about 14 dB *Eb=No* 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.
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 neighbouring transmitters we wish to use the smallest possible transmitter power.
Data Rate: This is a trade off 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.
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 *mid frequency 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.
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.

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 case code amplifier, with a passive filter and detector. The filter has a Q of 30, and center frequency of 18kHz. The circuit consumes 100µA at 5 volts (500µW).

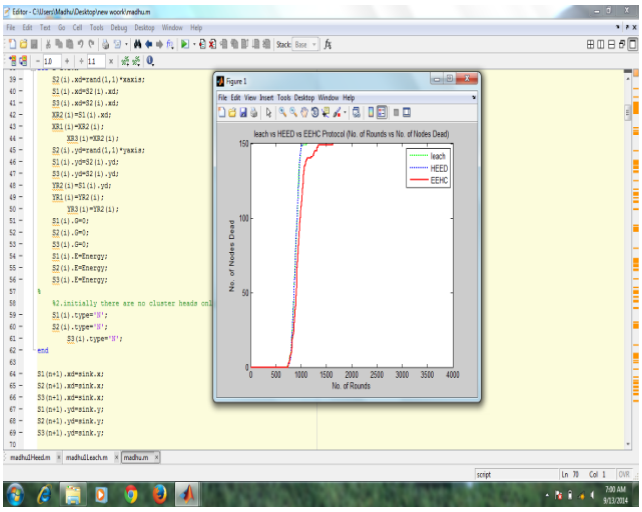
V. PROTOCOLS FOR HIGH-LATENCY NETWORKS

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 adaptive to changes in the number of nodes. Their energy efficiency can be improved by enabling low-duty-cycle operations on nodes, such as SMAC [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 SMAC 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.



```
        S2(i).xd=rand(1,1)*xaxis;
        S1(i).xd=S2(i).xd;
        S3(i).xd=S2(i).xd;
        XR2(i)=S1(i).xd;
        XR1(i)=XR2(i);
            XR3(i)=XR2(i);
        S2(i).yd=rand(1,1)*yaxis;
        S1(i).yd=S2(i).yd;
        S3(i).yd=S2(i).yd;
        YR2(i)=S1(i).yd;
        YR1(i)=YR2(i);
            YR3(i)=YR2(i);
        S1(i).G=0;
        S2(i).G=0;
        S3(i).G=0;
        S1(i).E=Energy;
        S2(i).E=Energy;
        S3(i).E=Energy;
    %
        %2.initially there are no cluster heads onl
        S1(i).type='N';
        S2(i).type='N';
            S3(i).type='N';
    end

    S1(n+1).xd=sink.x;
    S2(n+1).xd=sink.x;
    S3(n+1).xd=sink.x;
    S1(n+1).yd=sink.y;
    S2(n+1).yd=sink.y;
    S3(n+1).yd=sink.y;
```

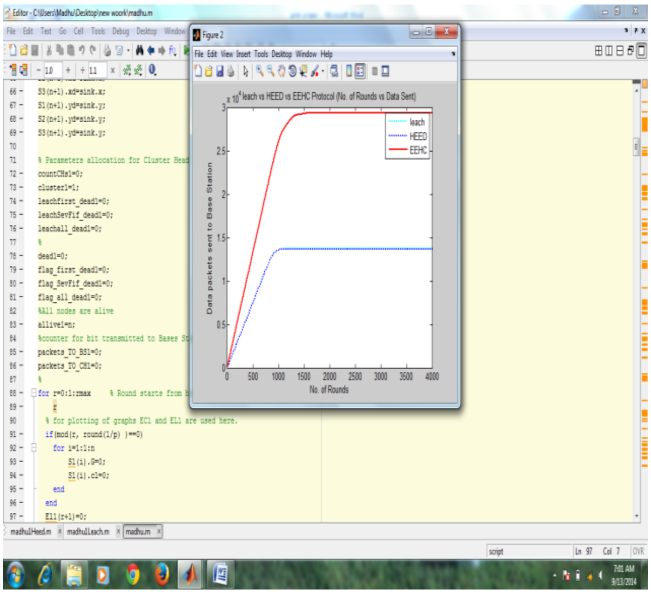
Fig. 2 comparision of Leach, Heed and Eehc protocols

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 time base, 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. 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.



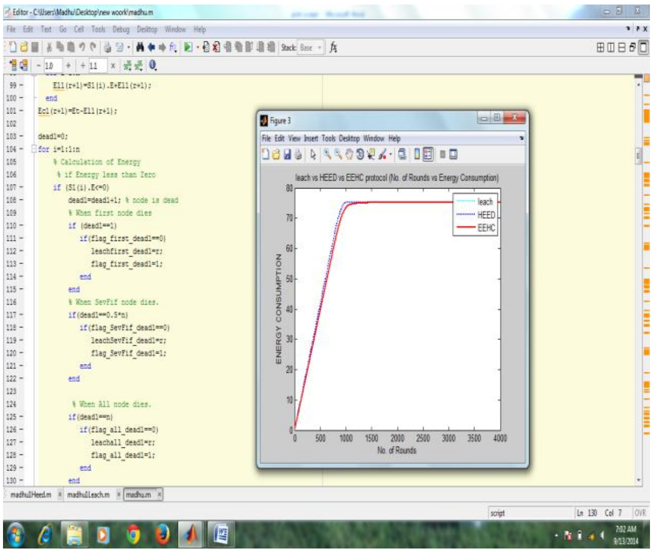
```
    S3(n+1).xd=sink.x;
    S1(n+1).yd=sink.y;
    S2(n+1).yd=sink.y;
    S3(n+1).yd=sink.y;

    % Parameters allocation for Cluster Head
    countCHs1=0;
    cluster1=1;
    leachfirst_dead1=0;
    leachSevFif_dead1=0;
    leachall_dead1=0;
    %
    dead1=0;
    flag_first_dead1=0;
    flag_SevFif_dead1=0;
    flag_all_dead1=0;
    %All nodes are alive
    allive1=n;
    %counter for bit transmitted to Bases St
    packets_TO_BS1=0;
    packets_TO_CH1=0;
    %
for r=0:1:rmax     % Round starts from h
        r
      % for plotting of graphs EC1 and EL1 are used here.
      if(mod(r, round(1/p) )==0)
        for i=1:1:n
            S1(i).G=0;
            S1(i).cl=0;
        end
      end
      El1(r+1)=0;
```

Fig 3 number of data packets transferred per 1000 rounds

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 neighbouring nodes, multi alteration algorithms can be applied for each node to calculate its relative position to some reference nodes. If super rnodels 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 super rnodels 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.



```
            El1(r+1)=S1(i).E+El1(r+1);
        end
    Ec1(r+1)=Et-El1(r+1);

    dead1=0;
    for i=1:1:n
        % Calculation of Energy
         % if Energy less than Zero
        if (S1(i).E<=0)
            dead1=dead1+1; % node is dead
            % When first node dies
            if (dead1==1)
               if(flag_first_dead1==0)
                  leachfirst_dead1=r;
                  flag_first_dead1=1;
               end
            end
            % When SevFif node dies.
            if(dead1==0.5*n)
               if(flag_SevFif_dead1==0)
                  leachSevFif_dead1=r;
                  flag_SevFif_dead1=1;
               end
            end

             % When All node dies.
            if(dead1==n)
               if(flag_all_dead1==0)
                  leachall_dead1=r;
                  flag_all_dead1=1;
               end
            end
```

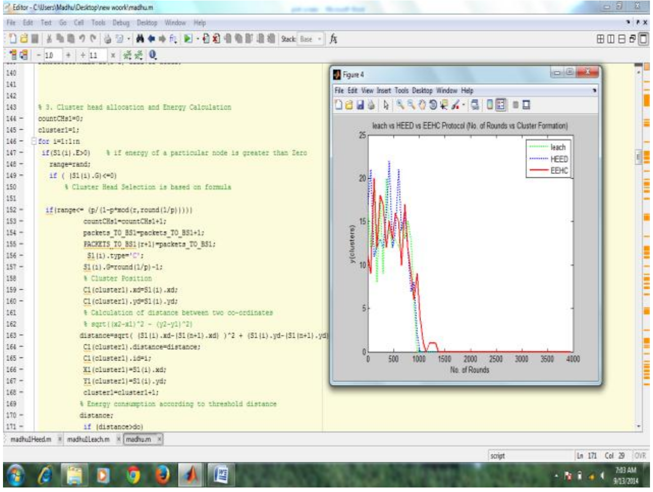
Fig 4 energy consumption per 500 rounds

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 drift, 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.

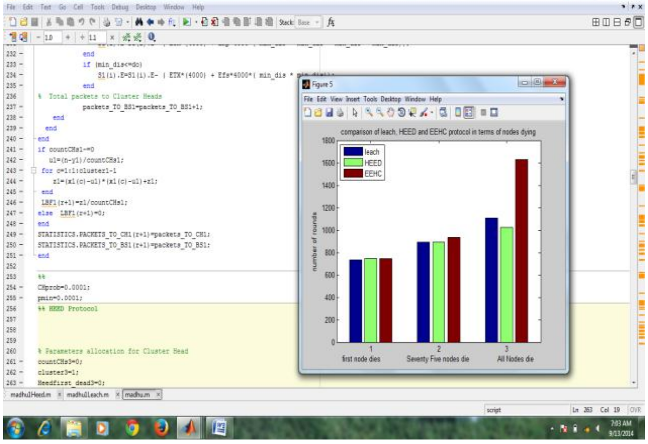


```
% 3. Cluster head allocation and Energy Calculation
countCHs1=0;
cluster1=1;
for i=1:1:n
 if(S1(i).E>0)    % if energy of a particular node is greater than Zero
   range=rand;
   if ( (S1(i).G)<=0)
       % Cluster Head Selection is based on formula

  if(range<= (p/(1-p*mod(r,round(1/p)))))
            countCHs1=countCHs1+1;
            packets_TO_BS1=packets_TO_BS1+1;
            PACKETS_TO_BS1(r+1)=packets_TO_BS1;
             S1(i).type='C';
            S1(i).G=round(1/p)-1;
            % Cluster Position
            C1(cluster1).xd=S1(i).xd;
            C1(cluster1).yd=S1(i).yd;
            % Calculation of distance between two co-ordinates
            % sqrt((x2-x1)^2 - (y2-y1)^2)
           distance=sqrt( (S1(i).xd-(S1(n+1).xd) )^2 + (S1(i).yd-(S1(n+1).yd)
            C1(cluster1).distance=distance;
            C1(cluster1).id=i;
            X1(cluster1)=S1(i).xd;
            Y1(cluster1)=S1(i).yd;
            cluster1=cluster1+1;
           % Energy consumption according to threshold distance
           distance;
            if (distance>do)
```

Fig 5 number of rounds

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 neighbours. 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.



```
              end
              if (min_dis<=do)
                  S1(i).E=S1(i).E- ( ETX*(4000) + Efs*4000*( min_dis *
              end
 %  Total packets to Cluster Heads
              packets_TO_BS1=packets_TO_BS1+1;
      end
    end
 end
 if countCHs1~=0
    u1=(n-y1)/countCHs1;
  for c=1:1:cluster1-1
      z1=(x1(c)-u1)*(x1(c)-u1)+z1;
  end
  LBF1(r+1)=z1/countCHs1;
 else  LBF1(r+1)=0;
 end
 STATISTICS.PACKETS_TO_CH1(r+1)=packets_TO_CH1;
 STATISTICS.PACKETS_TO_BS1(r+1)=packets_TO_BS1;
 end

 %%
 CHprob=0.0001;
 pmin=0.0001;
 %% HEED Protocol



 % Parameters allocation for Cluster Head
 countCHs3=0;
 cluster3=1;
 Heedfirst_dead3=0;
```

Fig 6 comparative study

VI. CONCLUSIONS

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

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