Wide Area Ocean Networks: Architecture and System Design Considerations

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ABSTRACT
Wide area ocean networks for monitoring and scientific exploratory purposes are in various stages of design; small-scale networks are already in various stages of deployment and testing. Clearly, cost-effective coverage is a primary underlying principle; arguably, such networks must therefore employ low-cost, energy-efficient mobile nodes**.** The first objective of this work is to broadly describe the architecture and system design considerations of such wide-area networks with mobile nodes; secondly, we introduce the APL/UW Seaglider capabilities and provide energy estimates for propulsion and data communications. We also discuss tradeoffs, and applications in ocean coverage, and optimization of sensor coverage within constraints of a power-efficient network.

Categories and Subject Descriptors
C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Distributed networks, Network communications, Network topology*.

General Terms: Algorithms, Measurement, Performance, Design, Experimentation.

Keywords: Underwater networking, Autonomous vehicles, Energy Efficiency.

1. INTRODUCTION
Architectural issues underlying the conceptualization and design of oceanic networks are of increasing importance due to imminent and planned deployment of sensors in the ocean for a variety of purposes; these include ocean observatories driven by scientific considerations such as NEPTUNE [1] or mission-oriented networks addressing commercial or security concerns such as SeaWeb [2]. Network design in such circumstances must contend with a variety of (conflicting) dimensions such as node mobility, coverage area/volume requirements, energy constraints, and communications link budget considerations [3-7]. Contending design methodologies can be compared within an overall cost-benefit analysis framework since wide-area ocean exploration remains a costly enterprise. Clearly, network nodes/resources should be located close to the anticipated pockets of interest in terms of scientific phenomena. Hence, if ocean floor exploration is the primary driver, a suitable architecture is to proliferate cabled seabed networks – whereby a set of nodes tethered by cables provide the power and communications infrastructure – such as the proposed NEPTUNE backbone. Similarly, for exploration of ocean sub-surface bulk phenomena, the presence of surface elements such as buoys and moored profilers is desirable, as indicated in Fig. 1 that shows a conceptual moored observatory.

While such an architecture solves the issues of power and bandwidth availability at critical node points, it incurs costly capital expenditures and cannot scale for large area/volume coverage. One way to achieve wide-area coverage at reasonable cost, is the deployment of an network that employs autonomous underwater vehicles (AUVs) which are battery powered, self-propelled (mobile) nodes. Such nodes provide many other advantages besides cost, including the flexibility to dynamically reconfigure network topology to localized events of interest as they occur. However, the current state-of-art in AUV design determines the limits of range and data transfer capabilities achievable and will dictate the density of AUVs needed for coverage.

Wide-area oceanic networks are typically comprised of two classes of sensor nodes:

1. Largely static with power tether: these will either reside on the sea-bed or float on the ocean surface (surface buoys) and serve as egress points for observed data to a shore station (either directly or via an intermediate satellite station)
2. Mobile AUVs that are lightweight, battery powered and capable of autonomous exploration. A good example is the Seaglider, developed by the Applied Physics Laboratory (APL) at the University of Washington (UW) and other vehicles in this class built

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by the Woods Hole Oceanographic Institution and Scripps Institution of Oceanography, respectively [8].

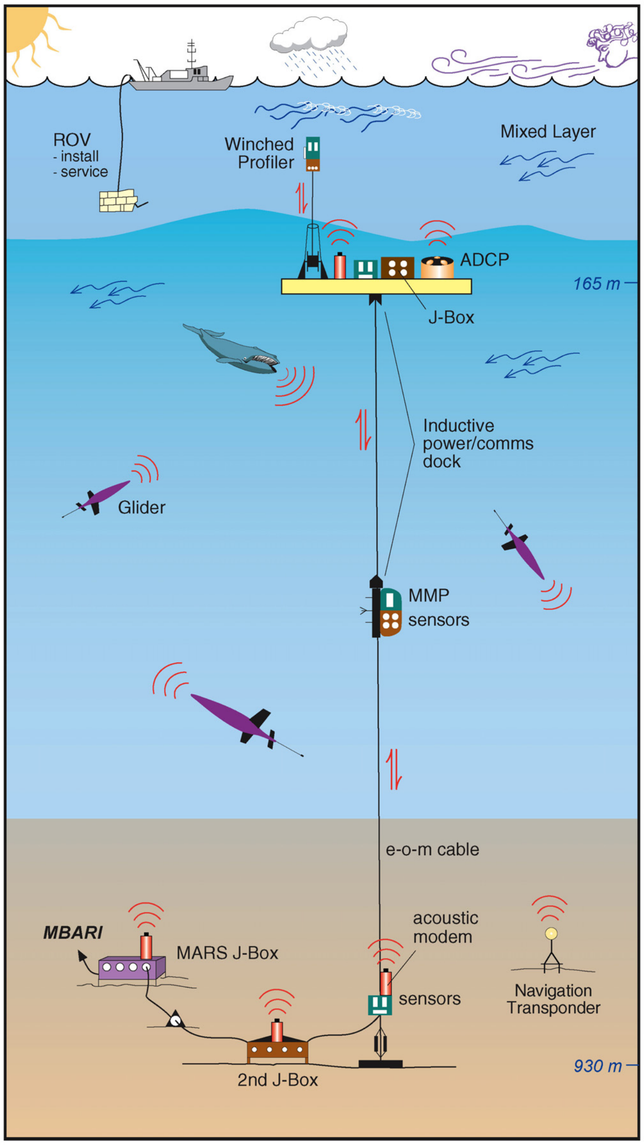

Figure 1: Moored Sensor Network with Seagliders planned for the MARS Observatory in Monterey Bay.

The purpose of this work is to introduce the APL/UW Seaglider as an AUV prototype that can explore ocean volumes with extremely modest energy requirements. Mobile nodes such as Seagliders have made wide area ocean surveillance at modest cost a possibility; once released from a surface vessel, they can be designed for vertical surveys of oceanographic data along a pre-determined trajectory for an extended duration subject to the available on-board battery energy.

We will also discuss a concept of operations for moored profiler networks composed of largely static nodes, and consider a hybrid network composed of both static and mobile nodes (see Fig. 1).

Our ultimate goal is to design underwater sensor networks that perform their mission optimally with long lifetime (best use of available energy).

2. NETWORK OVERVIEW

The underwater network under consideration is comprised of (see Fig. 1).

a) A network topology and architecture which will evolve out of a cabled backbone (that provides DC power on the order of 10s of kWs, and high-speed connectivity such as 1 GB Ethernet) along the ocean floor (at depths of 6 km), emanating from an on-shore gateway.

b) A mooring system with junction nodes at the top and bottom that support a vertical profiler. This has limited power (periodically charged when docked at its end points), gathers continuous data and is outfitted with an inductively coupled modem for real-time data transmission to shore.

c) A set of junction boxes on the seafloor and moored in the water column constituting the network's 1^{st}-tier nodes. These boxes are powered and contain acoustic transceivers; they will be sparsely positioned (approx. 100 km separation) along the backbone cable. Each junction box can act as a hub for connecting wired sensors as well as wireless sensors via 1-hop to form a local area network. For many lower power sensors, a wireless connection is the more economical.

d) Powered underwater unmanned vehicles (Seagliders) that will primarily function as range extenders for volumetric coverage beyond the 1-hop radius of 1^{st}-tier nodes; several of these can collaborate and reconfigure their formation to perform optimized environmental sampling and/or passive acoustic monitoring missions on an on-demand basis.

e) Topologically speaking, the core network will evolve as a *rooted tree* with (shore-based) gateways acting as a root node, and potentially multi-hop transmission of data from remote sea gliders to the root node (via 1^{st}-tier junction boxes) using other collaborating nodes in the vicinity (other Seagliders).

3. DESIGN CHALLENGES

From the above description, several system aspects are seen to be of immediate significance from the network design perspective:

- What are the geometrical considerations and traffic characterization for a 1-hop sensor network – i.e. network radius and node locations; how many sensor nodes and their respective traffic profiles (mean rates, max and min deviations, storage and processing capabilities etc)? Of particular interest will be modeling the profiler for data rate as a function of time if near real-time operation is a driving consideration.

- What are the capabilities of the Seagliders – i.e. maximum radius of operation and associated link/MAC layer protocols? An important component of this will involve modeling energy consumption as an integrated function of their navigation and communication suites, to suggest how efficiencies in both areas may be achieved.
- In what ways can the sensor network be reconfigured, expanded, or otherwise modified without a loss in performance? What configurations, topologies, and network routing schemes are conducive to scalability in terms of power and bandwidth usage, congestion control, and overall network robustness to disruptions?
- Successful sensor network design (topology, protocol stack and associated algorithms), must incorporate credible link models. It is well-known that the impact of unreliable links manifests itself at the higher layers, specifically on the MAC and routing protocols, significantly impacting aggregate sensor network performance. Specifically, one will have to characterize a) the channel rate vs. range/Doppler profiles as a function of frequency, bandwidth, transmit-receive geometry, ocean acoustic parameters etc., and b) theoretical upper bounds on link capacity to explore important trade-offs: since both available bandwidth and channel attenuation increase with frequency, an optimum frequency band/signal bandwidth for our environment can be computed.

We take preliminary steps towards answering some of these challenges in this paper.

4. NETWORK ELEMENTS

4.1 Seagliders

This is an APL developed autonomous vehicle, 1.8 meters long and weighing 52 kg with low hydrodynamic drag shape [9]. Seagliders are buoyancy-driven, relying on battery powered hydraulic pumps to bring about changes in buoyancy for generating thrust for propulsion. Typically, they move slowly through the water to conserve energy and achieve desired range or mission durations. Designed to operate at depths up to 1,000 meters, the hull compresses as it sinks, matching the compressibility of seawater (Fig. 2).

Seagliders can travel at varied angles – from gentle (e.g. 1:5) to steep (3:1). At gentle glide slopes the vehicle transits most efficiently in terms of battery consumption, while steeper slopes are used to maintain position and act as a "virtual mooring". Seagliders can gather conductivity-temperature-depth (CTD) data from the ocean for months at a time and transmit it to shore in near-real time via satellite data telemetry. Seagliders make oceanographic measurements traditionally collected by research vessels or moored instruments, but at a fraction of the cost.

Seagliders can survey along a transect, profile at a fixed location, and can be commanded to alter their sampling strategies throughout a mission (Fig. 3). In an on-going project funded by the Office of Naval Research, a modem developed by the Woods Hole Oceanographic Institution and a broadband hydrophone receiver are being integrated into the Seaglider.

Figure 2: The APL/UW Seaglider.

The Seaglider dives at an angle θ_g by simply reducing its volume and thereby it's buoyancy relative to its mass, as shown in Fig. 4. By design, the vehicle wings induce lift (L) and drag (D) forces to act, perpendicular and opposite to the direction of motion as shown in Fig. 4. The three forces - L, D, B are in dynamic equilibrium, resulting in a constant velocity descent. At the bottom of the dive, the glider increases its buoyancy (inflating a bladder to increase its displaced volume) via a pump, and begins to re-surface. The pitch angle θ_p is a control variable – at gentle glide slopes the vehicle transits more efficiently, and hence smaller θ_p and resultant glide angle θ_g is preferred. The sampling interval for data collection is programmable and can be altered during a mission. The data gathered on each dive is transmitted to shore in near-real time upon completion of each dive using satellite telemetry. A mission, i.e. a sequence of dives until battery exhaustion, can last several weeks, whereupon the Seaglider is reclaimed for future re-use.

Two-way communications from the Seagliders to satellite and shore are accomplished using two Motorola 9522 satellite modems via the Iridium network. Iridium modems use a direct-dial connection to a Linux workstation through a POTS telephone line or a backup Iridium modem. The connection speed for the Iridium modems is 2,400 bps with BPSK modulation. Once a connection is made, PPP (point to point protocol) is used to run IP (Internet Protocol) allowing the use of standard networking tools for communication and file transfer.

The primary Iridium unit contains an integrated global positioning system receiver and is turned off when not in use. The secondary unit is powered at all times and will accept incoming connections. Simultaneous connections are possible and the controller supports multiple PPP connections when increased bandwidth is required. Each modem, along with its power converter and antenna are mounted in waterproof housing on the Seaglider.

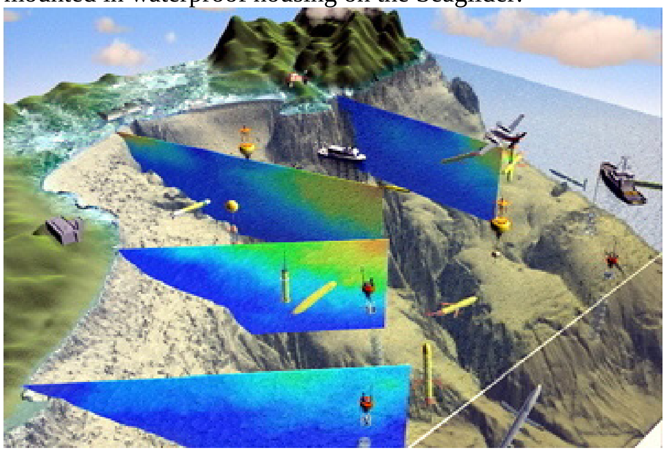

Figure 3: Example of mobile Seagliders measuring cross-sections of temperature, complementary to a fixed mooring, providing a continuous presence in the 3D ocean.

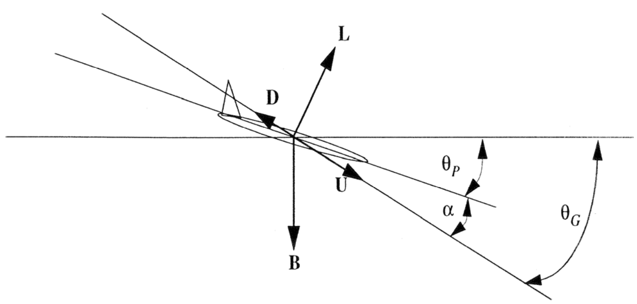

Figure 4: Seaglider's lift (*L*), drag (*D*) and net buoyancy (B) force diagram.

4.1.1 Principles of Operation

The Seaglider is assumed to execute a periodic symmetric sawtooth pattern from the ocean surface to a target depth *D* and back. Basic hydrodynamic theory [9] provides the following key quadratic relation to the angle of attack $\alpha=\theta_g-\theta_p$ where θ_p is the pitch angle:

$$K_{D1}\alpha^2 - K_L \tan\theta_g \alpha + K_{D0} = 0\,, \quad (1)$$

where K_{D1} and K_{D0} are drag coefficients, and K_L is a lift coefficient. They are estimated based on scale model observations.

Solving for α from Eq. (1), the velocity of the glider can be calculated from:

$$U = \sqrt{B\cos\theta_g / K_L\alpha} \quad (2a)$$

where the (net) buoyancy $B = \rho\,\Delta V$ where ρ is the density of sea-water (assumed constant) and ΔV is the change in volume of the vessel at the beginning of the dive.

For a target depth *D*, glide/dive angle θ_g and velocity *U*, the cycle duration is simply

$$T_c = \frac{2D}{U\sin\theta_g} \quad (2b)$$

For a dive angle of θ_g as in Fig. 4, the ocean area covered in one cycle equals $2D^2/\tan\theta_g$. A uniform sampling duration τ along the dive trajectory at velocity *U* translates to grid distance of $U\tau\cos\theta_g$ ($U\tau\sin\theta_g$) along the horizontal (vertical) dimensions, respectively. Thus, the number of sampling points in one cycle equals $2(D/U\tau\sin\theta_g)^2$. Assuming *r* bits of data is generated per sampling point, the net bit rate per cycle is $2r(D/U\tau\sin\theta_g)^2$.

4.1.2 Power Budget Analysis

In this analysis, we only consider the two components with the primary impact on battery drainage.

- **Energy Expended for Pumping**: The glider battery must provide the necessary energy for the hydraulic pump to inflate itself at the bottom of the dive for re-surfacing. At a depth *D*, the energy needed to cause a change ΔV in volume against an external hydrostatic pressure corresponding to the water column of depth of depth *D*, $P(D) = \rho g D$ (ρ is the density of sea water, *g* is the acceleration due to gravity) is given by $\rho g D \Delta V$. With a conversion efficiency $\eta(D)$ (of stored battery energy to mechanical energy) that is depth dependant, the actual battery energy expended is $\rho g D\Delta V / \eta(D)$ Joules/ cycle. Table I in [9] suggests that $\eta(D)$ improves with depth, but in our computations we will subsequently ignore this dependence.
- **Energy Expended for Data Uplink**: Using an estimate of the energy consumption per bit of data sent via Iridium uplink by E_{up} *(J/bit)*, the energy expended per cycle equals $E_{up}2r(D/U\tau\sin\theta_g)^2$ Joules/cycle**.**

Thus, assuming a net battery budget of E_B Joules for the glider at initialization, the total mission duration is $T_M = T_cN_c$, where N_c denotes the number of cycles in a mission, given by

$$N_c = \frac{E_B}{\rho g D\Delta V/\eta(D) + E_{up}\ 2r\ (D/U\tau\sin\theta_g)^2} \quad (3)$$

Hence using Eq. (2b) in Eq. (3) yields

$$T_M = \frac{E_B}{\frac{\rho g \Delta V}{2}\frac{U \sin\theta_g}{\eta} + \frac{E_{up} r}{\tau^2}\frac{D}{U \sin\theta_g}} \quad (4)$$

The above provides insight into optimization of the mission lifetime with respect to two design choices: D and θ_g. The first (second) term in the denominator is directly (inversely) proportional to $U \sin \theta_g$, representing a trade-off: energy efficient propulsion calls for lower θ_g whereas higher values of θ_g yield fewer data bits and hence lower energy required for communications. Thus mission duration T_M is optimized by determining the 1st order necessary conditions for the denominator of (4); differentiating with respect to $x = U \sin\theta_g$ yields

$$\frac{C_1}{\eta} = \frac{C_2 D}{x_*^2} \quad (5a)$$

where for convenience, $C_1 = \frac{\rho g \Delta V}{2}$, $C_2 = \frac{E_{up} r}{\tau^2}$. Hence, the optimum dive angle θ_g is obtained from

$$\sqrt{B/K_L \alpha}\sqrt{\cos\theta_g}\,\sin\theta_g = \sqrt{\frac{C_2}{C_1}}\sqrt{D\eta} \quad (5b)$$

Squaring (5b), substituting for B, C_1, C_2 in Eq. (5b) yields, after simplification, the following cubic equation in $x = \cos\theta_g$

$$x^3 - x + A = 0 \quad (6)$$

where $A = \frac{2K_L \alpha\eta}{(\rho\Delta V)^2 g}\frac{E_{up} r}{\tau^2} D$. In the table below, we provide the optimal glide angle θ_g as a function of the target depth D, assuming all other parameters are constant (independent of depth) with values as follows (several of these are obtained from [8]):

$K_L = 0.00224$; $r = 8$ bits/sample; $\tau = 10$ sec.; $\alpha = 0.3$ rad;

$\rho = 1027$ kg/m^3; $\eta = 0.5$; g = 9.8 m/s^2; E_{up}= 35 J/kByte;

and $\Delta V = 840$ cm^3.

Depth *D* (km)	**Optimum θ_g (deg.)**
1	3.24
300	5.67
500	7.34
1,000	10.42

Table 1: Optimal glide angle θ_g as function of target depth *D*

4.2 WHOI Micromodem

This modem (Fig. 5) developed at the Woods Hole Oceanographic Institution will be used in our network backbone, deployed on Seagliders, as well as on seafloor and moored nodes (See [11] and http://acomms.whoi.edu/). As a firmware upgradeable modem, this is a simple, yet powerful device, enabling data rates of 80-5400 bps and a good level of control via software, such as

- Acknowledgement of individual data packets/frames.
- Ability to measure travel time to specific units or determine if they are in range.
- Remote control of hardware output lines on the modem (e.g. to drop a weight).
- Low power operation modes.
- Interface to on-board A/D converter.
- Tracking of relative Doppler between source/receiver.
- Built-in data FIFO flash buffer for data storage prior to transmission.
- Multiple transmit rates using frequency, or phase shift keying, and one receive data rate. Frame integrity is protected with a cyclic-redundancy check (CRC).
- Reporting of real-time clock time, start/end of packet transmission, and ACK that a frame has been received correctly by another unit.
- Transponder navigation capability.

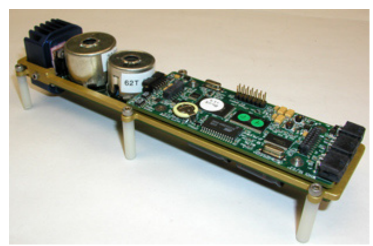

Figure 5: The WHOI MicroModem

4.3 Moored Profiler

The moored sensor network (see http://alohamooring.apl.washington.edu) is an APL design for use with seafloor observatories with power and communications provided by a connection to shore via electro-optical cable [1]. This system will address the challenge of sampling the ocean with both high temporal and vertical resolution. The mooring will consist of three main components (Fig. 1): a near-surface float at a depth of 165 meters with a secondary node (junction box – J-Box) and suite of sensors; an instrumented motorized moored vertical profiler moving between the seafloor and the float that will mate with a docking station on the float for battery charging; and a secondary node (J-Box) on the seafloor with a suite of sensors. Both secondary nodes will have remotely operated vehicle (ROV) mateable connectors available for guest instrumentation. The profiler will have real-time communications with the network via an inductive modem that will provide remote control functions to allow the sampling and measurement capabilities to be focused on the scientific features of greatest interest. The power and two-way real-time communications provided by cabled seafloor observatories will enable this sensor network, the adaptive sampling techniques, and the resulting enhanced science. This NSF-funded project to develop ocean observatories technology will be tested in Puget Sound in summer 2006 and deployed on MARS cabled node in Monterey Bay in summer 2007.

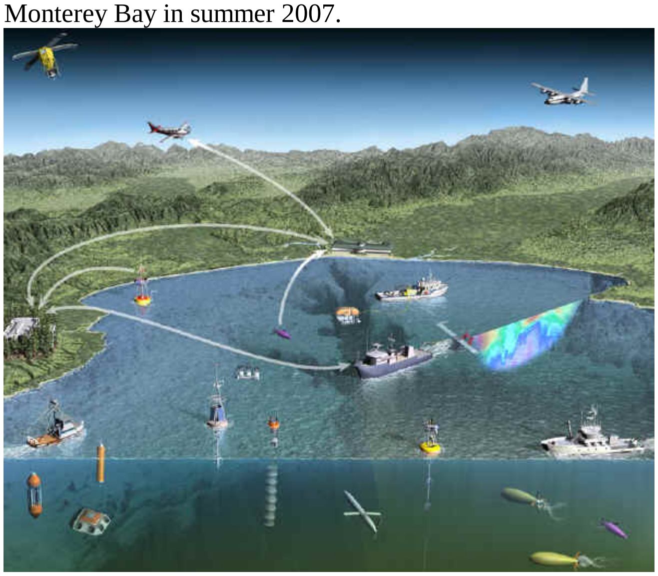

Figure 6: Schematic diagram showing the synergistic integration of in situ and remote sensing sensors in Monterey Bay.

5. APPLICATIONS

5.1 Ocean Observation

An example science concept of operations for the above network is to have multiple mobile Seagliders flying around the fixed mooring system with the vertical profiler, sampling temperature and salinity, within the infrastructure provided by an underwater acoustic network. The acoustic sensors will monitor the ambient sound (via listening) of marine mammals, and enable acoustic tomography. Preparations are underway for such an experiment (operations will be conducted in Monterey Bay, California). We selected Monterey Bay simply to leverage three assets: the existing Monterey Bay Ocean Observing System operated by Monterey Bay Aquarium Research Institute (MBARI), the NSF-funded Monterey Accelerated Research System (MARS) cabled observatory system, and the mooring system described above (Fig. 6).

5.2 Sensor Coverage

Another application relates to ongoing work at APL/UW on sensor coverage, and incorporation of communication constraints, and network topology and design, into sensor coverage and target tracking applications.

Distributed sensing systems must be designed such that individual sensors work together to accomplish the mission of the overall system, e.g., surveillance, tracking, etc. This may be through a centralized approach, where the results from individual sensors are sent to a central location for fusion processing, or a distributed approach, where each sensor platform has knowledge about the entire field of sensors and can make collaborative decisions about next actions.

In order to optimize the operation of a field of sensors (in either a centralized or distributed concept of operations), it is important that the decision making process include some form of sensor performance prediction, or sensor "coverage" prediction. For example, if we consider a field of passive (i.e., listening only) sensors whose mission is to detect with maximum probability any transiting sound source, the design of the field deployment pattern must include some estimate of how far away sound sources will be able to be detected from each of the sensors such that gaps in the coverage are minimized and detection probability is maximized. In the same vein, such coverage predictions are important in order to minimize expended resources such that the detection coverage is not overly redundant. In underwater scenarios, knowledge of the environmental parameters that govern sound propagation (e.g., sound speed profile, bottom forward loss vs. grazing angle, etc.) are key inputs to models that predict transmission loss (and hence system performance), and need to be known accurately for good system optimizations to occur.

In underwater systems, there are some subtle yet important differences between passive (previously described) and active (i.e., transmitting energy into the water and listening for target echoes) system performance prediction. Systems consisting of passive-only sensors usually need only consider the aggregation of the individual sensors' coverage patterns. Active systems, however, have a higher level of complexity, especially in the "multistatic" case where multiple transmitters' transmitted energy can be received on multiple receivers. Asset placement algorithms for multistatic active systems, therefore, become more complex since they need to consider the interplay between all emplaced sources and receivers, and the performance of all the various interdependent sensor deployment options.

Algorithms that take into account sonar performance prediction in order to design optimal multistatic active sonar fields are in development [12, 13]. These methods are based on recent developments in the field of computational intelligence, and present flexible methods for solving large-dimensional optimization problems.

5.2.1 POWER-EFFICIENT NETWORKING

For distributed systems, the method of information communication is also a key system parameter. This is true whether all information must be sent to a central node for fusion processing, or if all nodes are monitoring the performance of other nodes for distributed operations. Here, we assume that all communication and networking is achieved via underwater acoustic communications. The power required to communicate between the nodes will depend on their spatial distribution and on local environmental conditions. For the sensor network to have a long lifetime, it is crucial that finite battery power be used in an optimal manner.

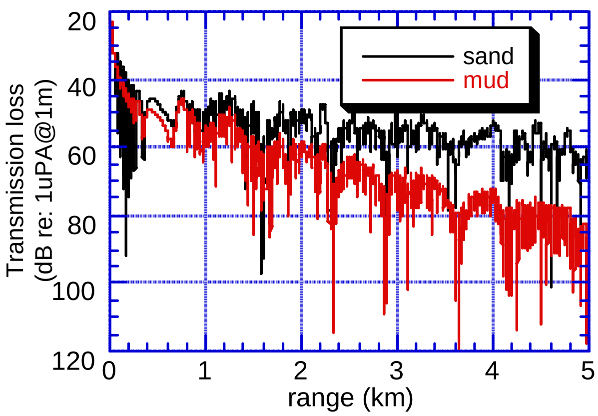

Figure 7: Effect of varying bottom type: Kauai sound speed profile; source/receiver at depth of 90 meters, water 100.7 meters deep.

Two basic acoustic communications strategies might be considered for a distributed system. In a direct access approach, each node can communicate directly either to the other nodes or to the central node. Alternatively, a relaying strategy may be adopted. In relaying, the transmission power need only be sufficient for the message to be received at neighboring nodes. The message is then forwarded to other nodes or to the central node. From the standpoint of power efficiency, relaying may be preferred particularly in a high-loss environment. The cost of relaying is a reduction in the over-all data throughput.

We illustrate power-efficient networking by a sample calculation using realistic environmental parameters. Acoustic transmission loss is calculated as a function of range in Figure 7. In the calculation, the water depth is 100 m and the water column is based on measurements made in the 2003 KauaiEx experiment [14]. Both the source and receiver are at depth 95 m and well below the mixed layer of warm water that extended to depth 60 m. At 10 kHz, a typical frequency for acoustic communications, there is only limited acoustic penetration into the seabed. Still, the composition of the seabed has a dramatic effect on the transmission loss. In Figure 7, two seabeds are considered, one an acoustically fast sand, the other an acoustically slow mud. Beyond a range of perhaps 1km, there is significantly more loss for the mud bottom. To achieve a required signal level at the receiver for these more distant ranges, high transmission power is required for the mud bottom. Moreover, the acoustic intensity falls off almost as inverse range-squared for the muddy bottom as one would expect for a spherical wave. In such a case, data relaying may offer significant savings in terms of power usage. By contrast, for the sandy bottom the acoustic intensity falls off more like inverse range as one would expect for a cylindrical wave. In such a case, direct communication between the nodes may be more feasible.

5.2.2 Multi-objective Optimization

In designing an underwater sensor network that shares information via underwater acoustic communications, then, we are faced with basic conflicting tradeoffs. We wish to place our sensors in close proximity to each other such that the cost (in power) of sending information is small. Yet, we also wish to place sensors in positions such that their coverage redundancy is small (i.e., we want to optimally space the coverage patterns), leading to a small but effective number of deployed sensors (we assume that the cost of individual sensors is significant enough to warrant the desire for the smallest number of sensors possible).

Such multiobjective optimization problems do not have a single optimal solution if an *a priori* objective weighting is not specified. Instead, the set of solution tradeoffs must be examined, usually referred to as the set of Pareto-optimal solutions, or the Pareto "front." The multiobjective optimization problem for multistatic active sonar systems is being actively investigated by Ngatchou *et al.* [12]. There, the tradeoff between system cost (i.e., number of sensors) and sonar coverage is examined. In that work, a set of solutions is generated answering the question: for all possible system costs (assuming that sources cost $X and receivers cost $Y), what is the best possible sensor coverage? Absent *a priori* constraints about maximum allowable cost or minimum allowable coverage, the entire set of solutions can be presented to an operator who can then decide the proper operating point for system deployment (or at least be informed as to what is or is not possible for a given system cost).

The methodology of [13] could be extended to incorporate communications networking into the optimization algorithm. One option would be to decide on a fixed system configuration (numbers of sources and receivers), and trade off system coverage vs. system lifetime (through power usage for acoustic communications). As sensors are moved further apart, overall area coverage will likely increase, while system lifetime will decrease due to the added power required for communication.

Alternatively, the overall system design could be undertaken using all three objectives simultaneously: system cost, system coverage, and system lifetime. The three-dimensional trade-off space could then be presented to system planners in order to see what is possible with available systems of sensors, and what performance is achievable from a coverage and system lifetime perspective.

6. FUTURE RESEARCH DIRECTIONS

We will focus on the following items in our future work:

- *A full and accurate simulation model* of the link and multiple access layers for purposes of predicting aggregate network characteristics (throughput/delay).
- *Definition of a new MAC layer for control of node states* (transmit, receive, idle, sleep) that optimizes network performance while obtaining power efficiency (we will use bits/Joule as an integrated metric). For mobile parts of the network (Seagliders), this optimization will extend to platform positioning such that network connectivity is maintained. This work will extend previous sensor placement research performed by us in the past. The success of any developed protocol will depend critically on node synchronization – hence, algorithms for time transfer and acoustic ranging and localization must be evaluated for accuracy over the channel models.

7. ACKNOWLEDGMENTS

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