Acoustic Communications for Regional Undersea Observatories

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Abstract

Undersea observatories connected to shore with fiber-optic cable will provide scientists with long-term measurements from deep-ocean sensors. Proposed regional observatories include NEPTUNE which will traverse a three thousand kilometer path on the Juan de Fuca plate in the North Pacific. The NEPTUNE backbone includes nodes spaced approximately 100 km apart where additional branches may be added, and a variety of sensors supporting different scientific disciplines will located at each node and along the branches. The fiber optic and power cable creates a backbone that easily supports many smaller regions (cells) covered by wireless communication. An acoustic system extends the reach of the observatory in the area around each cell, allowing additional instruments to be added without installing dedicated cables. The utility of the wireless extension is highly dependent upon the range of the link, its energy efficiency and the total capacity of a cell. The objective of this paper is to explore these issues and discuss design, implementation, and performance of the wireless network.

I. INTRODUCTION

The concept of a permanent, long-term, scientific presence in the deep ocean has received significant attention over the past several years [1]. There is a growing consensus among oceanographers that long-term measurements made over decades will bring about advances in understanding deep-ocean geology, biology, and chemistry. Interest in long-term sampling has already resulted in the development of two shallow-water observatories: LEO-15, which has been in place for over five years off New Jersey, and the recently installed Martha's Vineyard observatory [2].

Proposed deep-water observatories fall into two categories, those wired to shore with cables, and others that use surface buoys and satellite telemetry. Examples of buoy-based efforts include a Japanese project [3] and designs proposed as part of the Dynamics of Earth and Ocean Systems (DEOS) program [4]. Cabled deep-ocean systems include the Hawaii-2 Observatory (H2O), which uses a retired trans-Pacific telephone cable as an access point for seismology and other disciplines [5].

The proposed NEPTUNE observatory [6] will differ significantly from H2O in that it will be based on modern internet technology. However, the ROV installation techniques developed for H2O will be used extensively for NEPTUNE. While advanced power and optical communication technology will allow the long cables to circle the Juan de Fuca plate (Fig. 1), the deep-ocean ROV will be key to the system's installation and maintenance. Deep-ocean ROVs such as JASON [7] will be used to install, remove, and service instruments and junction boxes on the sea floor. While the use of ROVs for deep ocean system installation is becoming routine, it continues to be expensive because a large vessel and a team of operators must support its sophisticated winch, power and communications system. Thus, there is significant motivation to develop a wireless interface to connect instruments with moderate power and data requirements to the cabled network. This is particularly true for sensors placed several kilometers from a node. While connecting an instrument to a junction box 50-100 m away with an ROV is straightforward, laying several kilometers of cable is significantly more difficult and expensive.

Wireless communications is a low-cost, though lower performance, alternative to a hard-wired connection to the backbone. An instrument using a wireless connection is off the power grid, which is a significant disadvantage for long-term (multi-year) deployments and power-intensive sensors. Thus the wireless connection must be extremely efficient in terms of energy expended per bit of transmitted information. While advances in electronics and sensor technology have reduced, and will continue to reduce, the power requirements of oceanographic instruments, the physics of acoustic propagation and basic limits in communication theory ultimately bound the power efficiency of the wireless link. Thus not all sensors are appropriate for wireless connections.

We propose a design for the wireless extension to the observatory that will fully exploit both the power and bandwidth available at each node. The bandwidth allows use of multi-channel arrays that collect all of the acoustic energy available at the receiver, reducing the transmitted power required at a remote sensor. The relatively large amount of power available at the fixed node allows use of very low noise electronics and high-speed, high dynamic-range sampling. This allows the node to operate across a broad frequency band so that acoustic connectivity is available at different ranges.

The shore side of the wireless system will be fully integrated with the data management portion of the observatory. The wireless sensors will be operated through a central station that includes the demodulation, detection and data layers of the modem and then connects with the demultiplexer that handles data from the wired sensors over the fiber-optic link. A terrestrial analogy for the proposed system is a cellular telephone network where the antennas are physically separated from the receiving system. Long separation of antennas from receivers is impractical at radio frequencies, but feasible at ocean acoustic frequencies. The electronics required at each fixed node is very simple and includes only sampling, time-stamping, and conversion to internet protocol. All processing is done on shore using inexpensive general-purpose workstations running portable software. The acoustic receiver deployed in the ocean must be designed to a very high standard of reliability to minimize the possibility of failure, but its simplicity makes that goal attainable.

The paper is organized into several sections. In Section II the data rate requirements are reviewed and in Section III a design approach is described. Section IV includes a description of the proposed communication system including modulation methods, multi-user access and routing. Previous results and propagation modeling are also included to illustrate potential performance. Section V includes general discussion and concluding remarks.

II. REQUIREMENTS

An important initial objective in the design process for the acoustic network based around a fixed node (Fig. 2) is determining which sensors are good candidates for a wireless connection. The NEPTUNE design studies have identified the data rates for different sensors that may be connected to the nodes, and the rates span a tremendous range, from a few kbytes to several Gbytes per day [6]. Several other studies have examined the feasibility of acoustically-linked observatories, including the DEOS program [4]. Recently a proposal to use acoustic communication to telemeter selected data from the ocean floor to a buoy has been written by a group from the Woods Hole Oceanographic Institution and the University of Washington (R. Detrick, et. al., 2002). These sources and others provide a list of potential data sources suitable for the acoustic link.

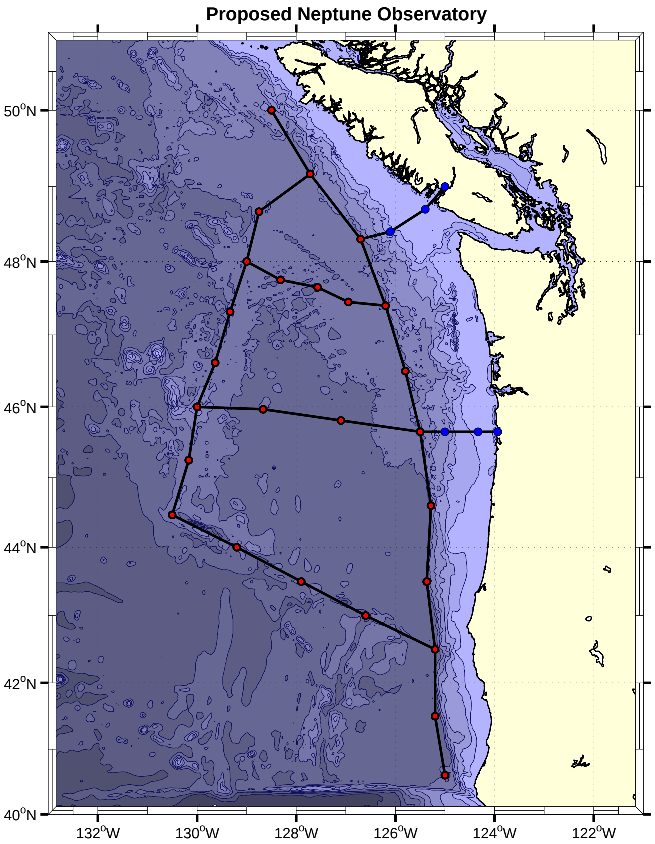

Fig. 1. Proposed NEPTUNE cable routes and node locations spanning the Juan de Fuca plate and terminating on shore at Port Alberni, British Columbia in the north, and Nedonna Beach, Oregon. Most of the nodes are between 2000 and 3000 m deep. (Node location information courtesy Bruce Howe, APL/UW.)

1. Hydrothermal vent sensor suite including ADCP, CTD, precision pressure, chemical and flow. Total estimated data per day is 0.5 Mbytes.
2. One sample-per-second seismometer data sampled on 3 channels. Total estimated data per day is 4 Mbytes.
3. A subset of broadband seismometer data corresponding to specific events detected locally at the sensor, or at cabled sites. One-half hour of data corresponds to approximately 3.3 Mbytes.
4. Electric field measurements made twice per minute. Estimated data per day is less than 20 kbytes.

The practicality of acoustic transmission for these applications depends upon the power required to reliably send the data to a cabled node. Realistic data rates at several kilometers may be on the order of 10 kbits per second and require ten watts of power. At this rate 0.5 Mbytes takes 400 seconds of transmission time, corresponding to a link efficiency of 1000 bits per joule. For one year that amounts to approximately 400 W-H, or less than 40 alkaline D cells. Achieving higher ranges, particularly beyond 10 km, will require significantly more power per bit. Additional performance estimates and propagation issues will be discussed in Section IV.

III. Design Approach

The undersea observatory node will include many multi-purpose sensors and perform minimal pre-processing of sensor data on the node. This takes full advantage of the bandwidth available on the fiber to separate sensing and processing into remote and on-shore functions. Acoustic receivers proposed for the nodes will be bandpass filtered and sampled at high rate and with as much dynamic range as possible to ensure that they are useful for marine mammal monitoring, acoustic tomography, ambient noise studies, and acoustic communication. The raw data will be sent through the network to shore where the actual acoustic communication processing will be done.

A subsea electronics module for the receiver is very simple and consists of only an analog front-end, digitizer and internet interface. The acoustic array itself includes as many broadband elements as may be physically supported at a given node. Sometimes there may be just one receiver, as in the case of a basic instrumentation node. Dual-use tomography and deep-ocean propagation studies may involve arrays several thousand meters long.

The transmit functions will also be separated such that the undersea portion of the system is simple and reliable. It will consist of a digital-to-analog converter, power amplifier and transducer. Supporting multiple transmit bands may require several transducers, essentially multiple copies of the same module with an appropriately matched power amplifier for a given transducer. Transmitters suitable for acoustic communication may not be multi-use, but frequencies from approximately 2-50 kHz are readily supported with two or three relatively small transducers. Frequencies from 50 Hz to 2 kHz require larger transducers, but because these frequencies are also of interest to acoustic tomography researchers, dual-use may be possible.

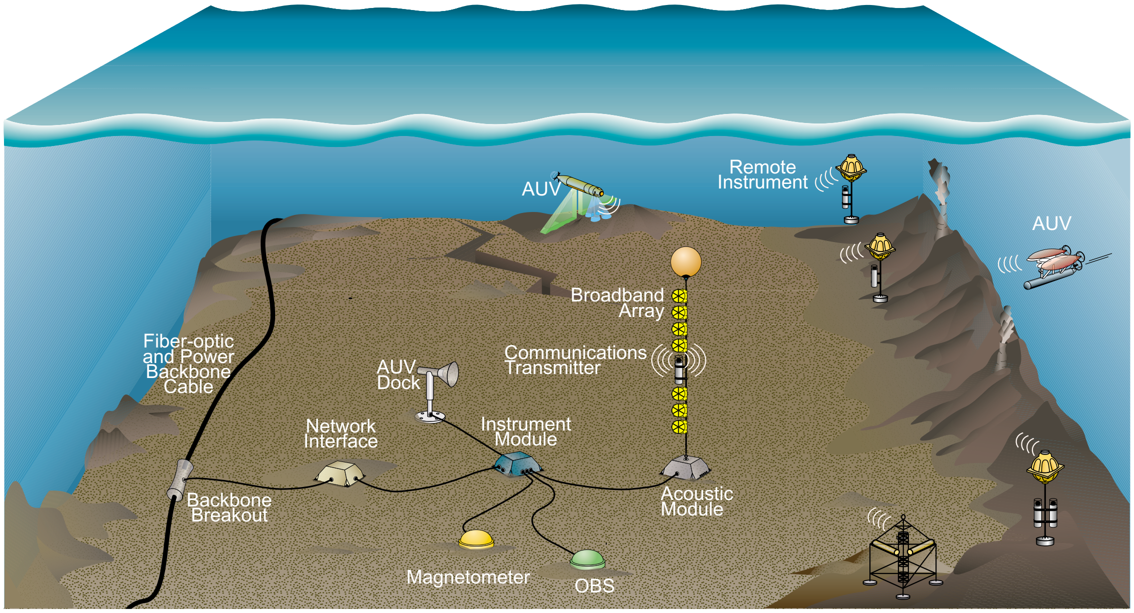

Fig. 2. Deep-ocean observatory concept showing cabled and local wireless access from fixed and mobile sensor systems.

IV. ACOUSTIC COMMUNICATIONS

Signal coding and modulation play an important part in achieving power efficiency at the physical layer. For the proposed observatory communications system the signal will be coherently detected phase-shift keying (PSK). This has the benefit of bandwidth efficiency which allows multiple information bits per Hertz of bandwidth, an important consideration in the bandwidth-limited underwater acoustic channel. The selection of a particular PSK signal constellation depends upon the signal-to-noise ratio. Commonly used signal constellations include BPSK, QPSK, 8-PSK and 16-QAM with one to four bits per Hertz efficiency respectively. However, achieving the high rates possible with the dense constellations requires estimating and removing the effects of time-varying multipath and Doppler. In this section phase-coherent acoustic communication development and performance is presented along with networking, multiple-access, and data link control.

A. Phase-Coherent Communication

The first high-rate phase-coherent underwater acoustic communication systems were used for vertical applications with directional transducers [8],[9]. In this application there is no boundary interaction and the channel has very little temporal spread. These PSK systems were not designed to remove the extensive inter-symbol interference (ISI) caused by multipath in the horizontal channel, and thus early attempts at high-rate communication where the range is many times the water depth generally employed M-ary frequency-shift keying (FSK) with symbol durations selected to be longer than the multipath delay.

Phase-coherent modulation for horizontal propagation in both deep and shallow-water was addressed by a series of experiments organized by Catipovic in the early 1990s. These tests culminated in the design of a new multi-channel adaptive equalizer structure optimized for the underwater channel [10],[11]. During the past ten years there has been significant additional work in high-rate phase-coherent communication by the authors and other investigators [12].

Two examples from different propagation regimes help to illustrate the range of performance possible with the proposed system. The first is from a recent (2001) high-rate, short-range test using a fixed bottom-mounted source and receiver. The symbol rate (and bandwidth) is 10 kHz and 16-QAM modulation is employed to yield a raw data rate of 40k bps. The water depth is only 15 m, and thus there is both surface and bottom interaction. However, the multipath is relatively stable, and as a result, adaptive equalization with 6 hydrophone channels from a short vertical array (0.5 m) provides high SNR output as shown in Fig. 3.

A second example is from [13], a 1996 test that included 1250 sps QPSK signals (2500 bps raw rate) transmitted at 2.25 kHz carrier in deep water offshore New England. In this test a partial convergence zone was present at a range of 35-44 km between source and receiver vessels. The receive vessel drifted very slowly while the source vessel motored at several knots. While only two rays were observed, they were both stable. Multi-channel adaptive equalization provided reliable detection using just 4 hydrophones spaced 6 meters apart [13].

These results and others presented in earlier work ([10] and [11]) demonstrate that acoustic communications has the potential to provide a solid physical layer for the wireless extension to the cabled observatory. While additional testing in this environment is required to quantify the actual performance of such a link with respect to range, frequency and array aperture, it is clear that high-rate links can be established at both short and long range.

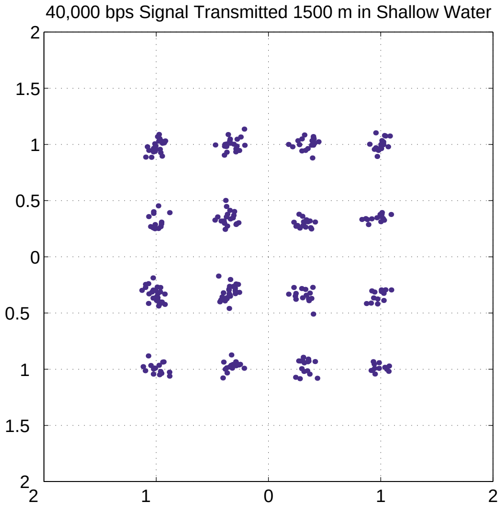

Fig. 3. 16-Quadrature Amplitude Modulation (QAM) signal constellation at the output of the multi-channel adaptive equalizer for a 1.5 km transmission in shallow water near Newport, RI. The bandwidth is 10 kHz and the 1 of 16 modulation provides 4 bits per Hz spectral efficiency to yield 40k bps raw throughput.

B. Propagation Modeling in the Juan de Fuca Region

Propagation of acoustic signals from a source located below the sound channel in the deep ocean is characterized by upward refraction. Consequently, a direct path may not exist from a bottom source to a bottom receiver. This is illustrated in Fig. 4 (top), where a 10 kHz directive source is located on the bottom and the transmission loss with respect to range is plotted. As range from the source increases, the receiver height above the ocean floor where only non surface-interacting rays are present also increases. In reality, there will always be reflected arrivals from the surface due to the sidelobes of the projector. These surface reflections may have a significant impact on receiver performance, depending upon their amplitude and rate of fluctuation. Fortunately, the use of a vertical array allows rejection of surface bounce in favor of the direct arrivals [13].

At 2 kHz significantly longer propagation may be expected and sufficient energy may be present at up to 50 km, depending upon the location of the receiver and the source level (Fig. 4, bottom). While the experimental results described in [10] and [13] show that high-rate phase-coherent communication is possible at ranges of 40 km or greater using 1-2 kHz carrier frequencies, bottom and surface interaction at ranges prior to where most of the reflections are stripped away can make reception very difficult [13]. Array processing is key to good performance in a strong multipath environment, and additional modeling that includes examination of surface reflections in this context will be required.

C. Acoustic Networking

The first task in the development of an underwater network is the choice of network topology. Two topologies are generally considered for undersea use: centralized and decentralized. In a centralized topology, the network users communicate via a central access point, in a manner that resembles a cellular mobile radio system [16]. In this case, the system design focuses on the choice of multiple-access strategy for sharing the communication channel. In a decentral-

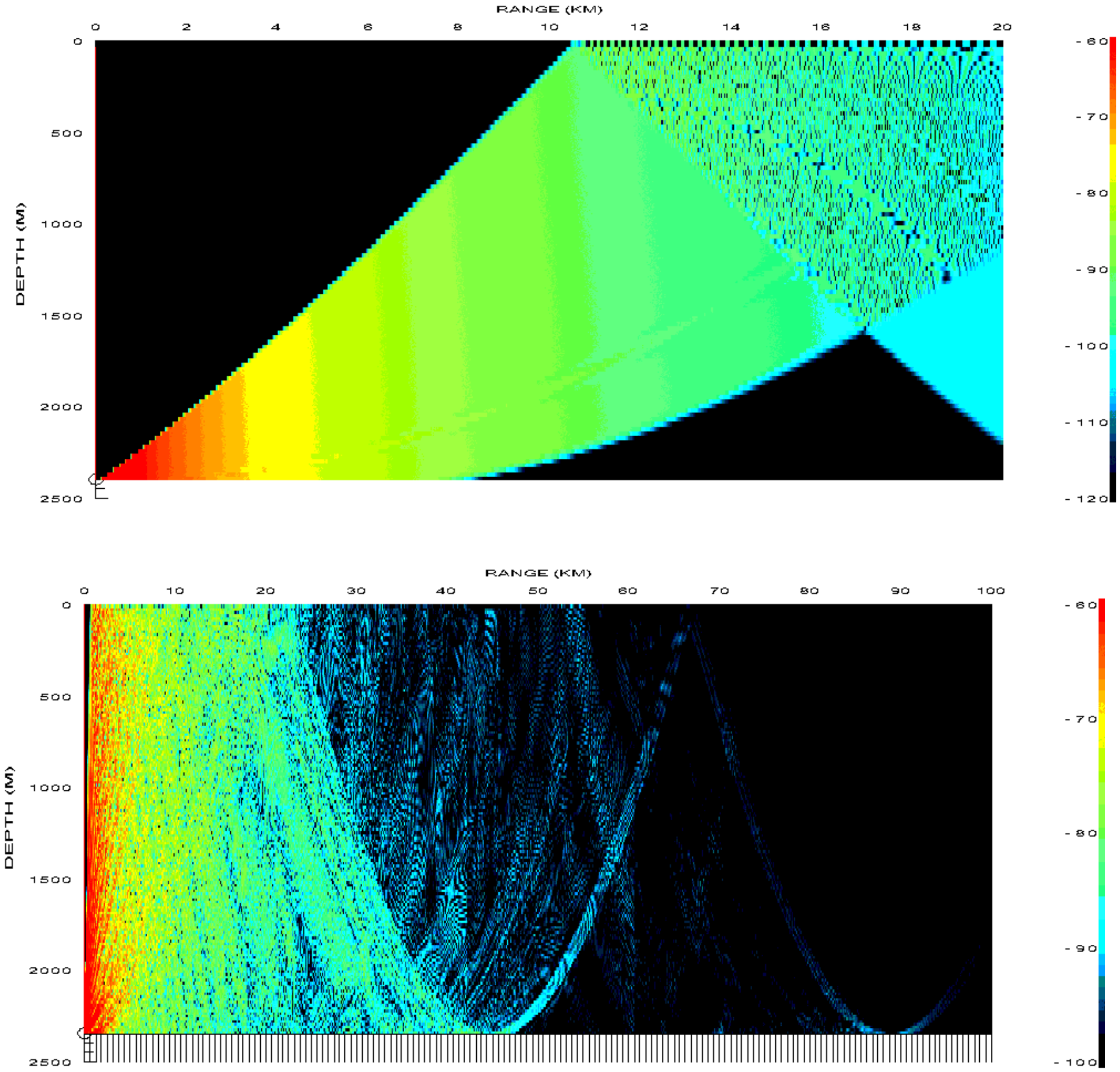

Fig. 4. Transmission loss at 10 kHz and 2 kHz for bottom-mounted transmitters in the Juan de Fuca area. Top: Transmission loss for a 10 kHz horizontally directive source over 20 km. (In this case only a narrow range of launch angles are traced in order to simplify the presentation.) Bottom: Transmission loss at 2 kHz over 100 km.

ized topology, the network users communicate by relaying information packets via multi-hop routes between the source and the destination. This type of network resembles an *ad hoc* wireless radio network [17]. The major design issue in this case is the development of routing protocols that minimize power consumption of battery-operated users or nodes.

The choice between a centralized and a decentralized network topology becomes more difficult when the costs and complexities of actual undersea systems are introduced. For example, it is currently very expensive to lay a 10 km cable to extend coverage from a node to a remote instrument. However, it may be ultimately less expensive than steaming to a remote site, recovering, changing batteries, and re-deploying one or more acoustic repeaters every year for a decade. Conversely, if the ship time is available as part of other planned turn-around cruises, the cost to recover and deploy fresh repeaters may be significantly less than the cost of laying cable.

The wireless network that augments a regional observatory will make full use of the fiber-optic cable and minimize acoustic routing whenever possible. However, when multiple instruments use the same repeater, an access control method is required. While repeater access control is similar to network node access control, the power constraints and computational limits of a self-contained battery-operated repeater mean that the actual approach may be different. For example, code division multiple access (CDMA) is very attractive because it allows random access by multiple users without synchronization, but in general it will result in a higher peak computational requirement than time-division multiplexing.

D. Multiple-Access Acoustic Communication

In the design of a communication network for an environment that is broadcast by nature, the first step is the design of a multiple-access strategy. FDMA, TDMA and CDMA (frequency, time, and code-division multiple-access) are the primary candidates for broadcast channels. While CDMA yields no additional system capacity (number of users supported within a given bandwidth) on an ideal additive white Gaussian noise channel [18], it has an advantage when using time-varying, frequency-selective channels if high-resolution direct-sequence spread-spectrum signals are employed. The advantage accrues through exploitation of multipath diversity via decision-feedback equalization or rake filtering.

Another type of diversity, called macro-diversity is also available with CDMA. Since there is no frequency division between adjacent base stations, two (or more) base stations can hear the same mobile unit that is mid-way between them. By exchanging information about the signals received from the mobile, the base stations can decide which version to keep, or even perform signal combining to achieve better receiver performance. In the proposed NEPTUNE scenario the nodes are 100 km apart and only low-frequency communications would be observed at adjacent nodes. However, there are several locations being considered for denser sampling that may have fixed nodes as close as 10 km. In this case macro-diversity could be employed for either AUVs or remote instruments whose signals reach more than one node.

CDMA has several other advantages. In particular, this technique eliminates the need for elaborate frequency reuse planning, thus opening the way for an easy expansion of the network to a larger area of coverage. Secondly, CDMA is characterized by a soft capacity limit, not present in either frequency, or time-division multiple-access. Because the signals of other users are modulated using different signature waveforms, they appear (almost) as white noise to the user of interest. Hence, when a new user joins the system, its presence is experienced as an increase in the background noise level, and it does not lead to an abrupt interruption in communications. When using CDMA, there is no need for guard intervals, which are often necessary for underwater acoustic channels with unpredictable delays. Finally, spread-spectrum signals are inherently immune to narrowband jamming.

These benefits of CDMA, together with the recognition of channel distortions, have motivated an earlier study of spread-spectrum modulation for underwater acoustic communications

[15]. This study has shown that a direct-sequence spread-spectrum modulation is an advantageous technique to use on underwater acoustic channels, provided that the channel time-variation can be accurately tracked. This task is made difficult by the fact that neither the time-variation nor the multipath spread can be neglected in comparison with the bit duration. Consequently, the majority of traditional CDMA detection methods are not directly applicable to the acoustic channel. To fully exploit the capabilities of direct-sequence spread-spectrum signaling in a CDMA scenario, adaptive chip-rate filtering and equalization must be employed. The principles of adaptive chip-rate processing suitable for mobile or fixed undersea links have been developed in [19] and [20].

E. Data Link Control

In communication channels where the physical link has poor performance (the underwater channel, particularly where users are mobile, is in this category), error correction is better performed at the data link layer than at higher layers of a network architecture. Underwater acoustic modems that are currently available operate in half-duplex mode, and for this reason, automatic repeat request (ARQ) schemes based on the "Stop and Wait" protocol are favored. These schemes can improve the overall throughput despite the overhead that they create. However, the ARQ protocol parameters (packet size and time-out intervals) have to be chosen carefully in accordance with the given network scenario, in order to achieve the optimal efficiency.

Power control is also an important issue when designing a network for battery-operated units. Network optimization here is characterized by a trade-off between the quality of service and energy consumption. Integrating power control into the overall data link control protocol has been recognized as a means for increasing the capacity of a wireless network [21]. A protocol that includes power control appears to be the solution for this underwater acoustic application. In addition to battery conservation, power control is important for CDMA systems which are sensitive to the near-far effect. Preliminary results [20] have shown good system performance when interference level is kept within 10 dB of the desired signal, which is easily achievable with power control.

V. CONCLUSION

The design of a hybrid cabled-wireless undersea communication network will build upon communication network architecture used in similar terrestrial systems. However, fundamental limitations of underwater acoustic channels will necessitate the use of dedicated communication methods and new network protocols. These limitations include the low system bandwidth, the low propagation speed of acoustic waves, and the fact that the remote instruments are power constrained.

Despite the difficulties inherent in underwater acoustic communication, previous work has shown that a wireless link from remote instruments to a cabled node will provide a realistic option for system users. The performance of that link will depend to a large degree on the acoustic array placed at the fixed node. Multi-element arrays with large aperture have been used to demonstrate phase-coherent acoustic communication in a number of environments, from short range (Fig. 3), to basin scale [22].

The deep-ocean observatory must balance the cost of wiring individual sensors versus the cost of infrastructure for the acoustic link. At ranges of several kilometers the acoustic link will likely be advantageous for certain types of sensors, particularly low-rate temperature and chemical sensors used to monitor vent activity. As range increases the acoustic receiver must span more of the water column and it will require more transmitted power per bit. However, at certain nodes large dual-use arrays may be available as acoustic receivers, reducing the cost of dedicated hardware and increasing the range of the acoustic link around each cabled node.

VI. ACKNOWLEDGEMENTS

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