Seaweb Underwater Acoustic Nets

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ABSTRACT

Seaweb networks use digital signal processor (DSP)-based telesonar underwater acoustic modems to interconnect fixed and mobile nodes. Backbone nodes are autonomous, stationary sensors and telesonar repeaters. Peripheral nodes include unmanned undersea vehicles (UUVs) and specialized devices such as low-frequency sonar projectors. Gateway nodes provide interfaces with command centers afloat, submerged, ashore, and aloft, including access to terrestrial, airborne, and space-based networks. Seaweb command, control, communications, and navigation (C^3N) technology coordinates deployable assets for accomplishing given missions in littoral ocean environments. A series of annual experiments drives seaweb technology development by implementing increasingly sophisticated wide-area networks of deployable autonomous undersea sensors.

INTRODUCTION

Digital signal processor (DSP) electronics and the application of digital communications theory have substantially advanced the underwater acoustic telemetry state of the art [1]. A milestone was the introduction of a DSP-based modem [2] sold as the Datasonics ATM850 [3 and 4] and later identified as the first-generation telesonar modem. To promote further development of commercial off-the-shelf (COTS) telesonar modems, the U.S. Navy invested small business innovative research (SBIR) funding and Navy laboratory support with expectations that energy-efficient, inexpensive telesonar modems would spawn autonomous undersea systems [5]. Steady progress resulted in the second-generation telesonar modem [6], marketed as the Datasonics ATM875. Encouraged by the potential demonstrated with the ATM875, the Navy funded the advanced development of a third-generation telesonar modem [7] designated the Benthos ATM885.

Seaweb is an organized network for command, control, communications, and navigation (C^3N) of deployable autonomous undersea systems. Seaweb functionality implemented on telesonar hardware shows enormous promise for numerous ocean applications.

Offboard seaweb nodes of various types may be readily deployed from high-value platforms including submarine, ship, and aircraft, or from unmanned undersea vehicles (UUVs) and unmanned aerial vehicles (UAVs). The architectural flexibility afforded by seaweb wireless connections permits the mission planner to allocate an arbitrary mix of node types with a node density and area coverage appropriate for the given telesonar propagation conditions and for the mission at hand.

The initial motivation for seaweb is a requirement for wide-area undersea surveillance in littoral waters by means of a deployable autonomous distributed system (DADS) such as that shown in Figure 1. Future sensor nodes in a DADS network generate concise antisubmarine warfare (ASW) contact reports that seaweb will route to a master node for field-level data fusion [8]. The master node communicates with manned command centers via gateway nodes such as a sea-surface buoy radio-linked with space satellite networks, or a ship's sonar interfaced to an onboard seaweb server.

DADS operates in 50- to 300-m waters with node spacing of 2 to 5 km. Primary network packets are contact reports with about 1000 information bits [9]. DADS sensor nodes asynchronously produce these packets at a variable rate dependent on the receiver operating characteristics for a particular sensor suite and mission. Following *ad hoc* deployments, DADS relies on the seaweb network for self-organization including node identification, clock synchronization on the order of 0.1 to 1.0 s, node geolocalization on the order of 100 m, assimilation of new nodes, and self-healing following node failures. Desired network endurance is up to 90 days.

DADS is a fixed grid of inexpensive interoperable nodes. This underlying cellular network architecture is well suited for supporting an autonomous oceanographic sampling network (AOSN) [10], including C^3N for autonomous operations with UUV mobile nodes.

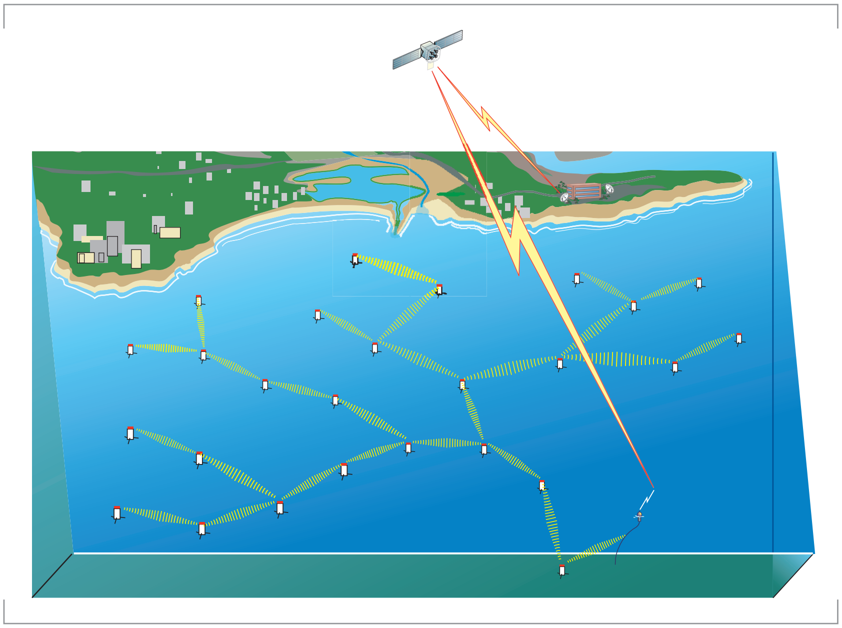

FIGURE 1. Seaweb underwater acoustic networking enables C^3N for DADS and other deployable autonomous undersea systems. Gateways to manned control centers include radio links to space or shore and telesonar links to ships.

CONCEPT OF OPERATIONS

Telesonar wireless acoustic links interconnect distributed undersea instruments, potentially integrating them as a unified resource and extending "net-centric" operations into the undersea environment.

Seaweb is the realization of such an undersea wireless network [11] of fixed and mobile nodes, including various interfaces to manned command centers. It provides the C^3N infrastructure for coordinating appropriate assets to accomplish a given mission in an arbitrary ocean environment.

The seaweb backbone is a set of autonomous, stationary nodes (e.g., deployable surveillance sensors, repeaters). Seaweb peripherals are mobile nodes (e.g., UUVs, including swimmers, gliders, and crawlers) and specialized nodes (e.g., bistatic sonar projectors).

Seaweb gateways provide connections to command centers submerged, afloat, aloft, and ashore. Telesonar-equipped gateway nodes interface seaweb to terrestrial, airborne, and space-based networks. For example, a telesonobuoy serves as a radio/acoustic communications (racom) interface, permitting satellites and maritime patrol aircraft to access submerged, autonomous systems. Similarly, submarines can access seaweb with telesonar signaling through the WQC-2 underwater telephone band or other high-frequency sonars [12]. Seaweb provides the submarine commander with digital connectivity at speed and depth and with bidirectional access to all seaweb-linked resources and distant gateways.

A seaweb server resides at manned command centers and is the graphical user interface to the undersea network as shown in Figure 2. The server archives all incoming data packets and provides read-only access to client stations via the Internet. A single designated "super" server controls and reconfigures the network.

Low-bandwidth, half-duplex, high-latency telesonar links limit seaweb quality of service. Occasional outages from poor propagation or elevated noise levels can disrupt telesonar links [13]. Ultimately, the available energy supply dictates service life, and battery-limited nodes must be energy conserving [14]. Moreover, seaweb must ensure transmission security by operating with low bit-energy per noise-spectral-density (E_b/N_0) and by otherwise limiting interception by unauthorized receivers. Seaweb must therefore be a revolutionary information system bound by these constraints.

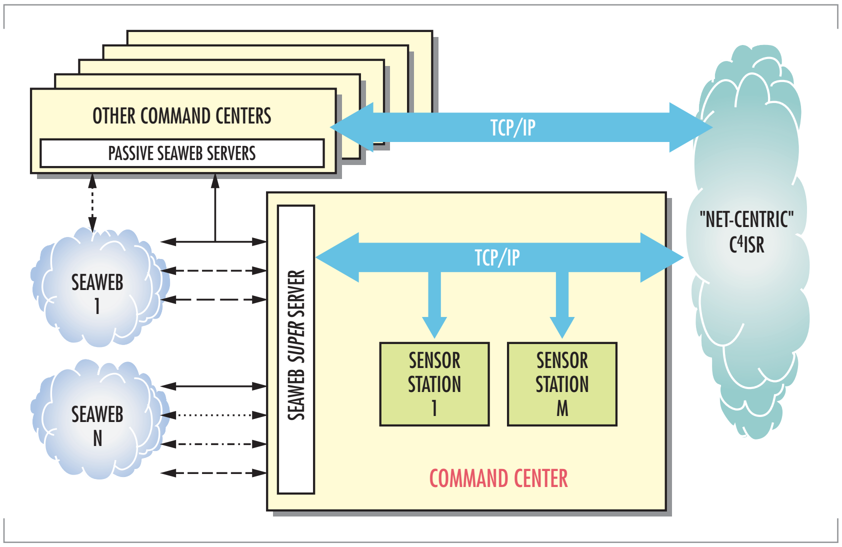

FIGURE 2. Seaweb extends modern "net-centric" interconnectivity to the undersea realm. Wireless underwater networks include gateway nodes with radio, acoustic, wire, or fiber links to manned command centers where a seaweb server provides a graphical user interface. Command centers may be aboard ship, submarine, aircraft, or ashore. They may be geographically distant and connected to the gateway node via space satellite or terrestrial Internet. At the designated command center, a seaweb "super" server manages and controls the undersea network. All seaweb servers archive seaweb packets and provide data access to client stations via the Internet. A single designated super server controls and reconfigures the network.

Simplicity, efficiency, reliability, and security are the governing design principles. Half-duplex handshaking [15] asynchronously establishes adaptive telesonar links [16] as shown in Figure 3. The initiating node transmits a request-to-send (RTS) waveform with a frequency-hopped, spread-spectrum (FHSS) [17] pattern or direct-sequence spread-spectrum (DSSS) [18] pseudo-random carrier uniquely addressing the intended receiver. (Alternatively, the initiating node may transmit a universal code for broadcasting or when establishing links with unknown nodes.) The addressed node detects the request and awakens from an energy-conserving sleep state to demodulate. Further processing of the RTS signal provides an estimate of the channel scattering function and signal excess. The addressed node then acknowledges receipt with a FHSS or DSSS acoustic response. This clear-to-send (CTS) reply specifies appropriate modulation parameters for the ensuing message packets based upon the measured channel conditions. Following this RTS/CTS handshake, the initiating node transmits the data packet(s) with nearly optimal bit-rate, modulation, coding, and source level.

Spread-spectrum modulation is consistent with the desire for asynchronous multiple access to the physical channel using code-division multiple-access (CDMA) networking [19]. Nevertheless, the seaweb concept

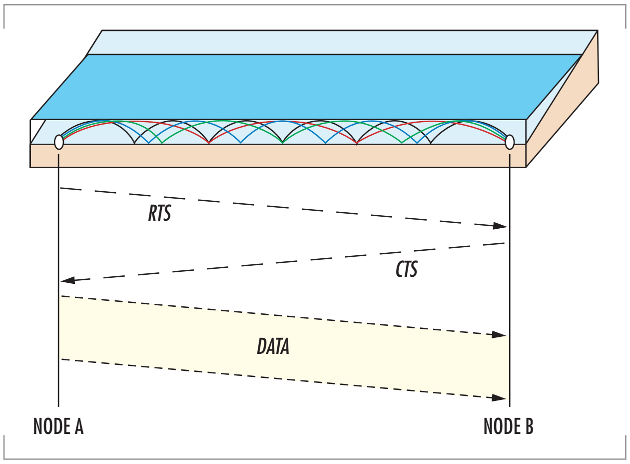

FIGURE 3. Telesonar handshake protocol for data transfer involves Node A initiating a request-to-send (RTS) modulated with a channel-tolerant, spread-spectrum pattern uniquely associated with intended receiver, Node B. So addressed, Node B awakens and demodulates the fixed-length RTS packet. Node B estimates the channel parameters using the RTS as a probe signal. Node B responds to A with a fixed-length clear-to-send (CTS) that fully specifies the modulation parameters for the data transfer. Node A then sends the data packet(s) with optimal source level, bit-rate, modulation, and coding. If Node B receives corrupted data, it initiates a selective automatic repeat request (ARQ).

does not exclude time-division multiple-access (TDMA) or frequency-division multiple-access (FDMA) methods, and is pursuing hybrid schemes suited to the physical-layer constraints. In a data transfer, for example, the RTS/CTS exchange might occur as an asynchronous CDMA dialog in which the data packets are queued for transmission during a time slot or within a frequency band such that collisions are avoided altogether.

The seaweb architecture of interest includes the physical layer, the media-access-control (MAC) layer, and the network layer. These most fundamental layers of communication functionality support higher layers that will tend to be application-specific.

At the physical layer, an understanding of the transmission channel is obtained through at-sea measurements and numerical propagation models. Knowledge of the fundamental constraints on telesonar signaling translates into increasingly sophisticated modems. DSP-based modulators and demodulators permit the application of modern digital communication techniques to exploit the unique aspects of the underwater channel. Directional transducers further enhance the performance of these devices [20].

The MAC layer supports secure, low-power, point-to-point connectivity, and the telesonar handshake protocol is uniquely suited to wireless half-duplex networking with slowly propagating channels. Handshaking permits addressing, ranging, channel estimation, adaptive modulation, and power control. The seaweb philosophy mandates that telesonar links be environmentally adaptive [21], with provision for bidirectional asymmetry.

Network supervisory algorithms can execute either at an autonomous master node or at the seaweb server. Seaweb provides for graceful failure of network nodes, addition of new nodes, and assimilation of mobile nodes. Essential by-products of the telesonar link are range measurement, range-rate measurement, and clock-synchronization. Collectively, these C^3N features support network initialization, node localization, route configuration, resource optimization, and maintenance.

DEVELOPMENTAL APPROACH

Given the DADS performance requirements, seaweb research is advancing telesonar modem technology for reliable underwater signaling by addressing the issues of (1) adverse transmission channel; (2) asynchronous networking; (3) battery-energy efficiency; (4) transmission security; and (5) cost.

Despite an architectural philosophy emphasizing simplicity, seaweb is a complex system and its development is a grand challenge. The high cost of sea testing and the need for many prototype nodes motivate extensive engineering system analysis following the ideas of the previous section.

Simulations using an optimized network engineering tool (OPNET) with simplified ocean acoustic propagation assumptions permit laboratory refinement of networking protocols [22] and initialization methods [23]. Meanwhile, controlled experimentation in actual ocean conditions incrementally advances telesonar signaling technology [24].

Seaweb experiments implement the results from these research activities with a periodic concentration of resources in prolonged ocean experiments.

The annual seaweb experiments validate system analysis and purposefully evolve critical technology areas such that the state-of-the-art advances with greater reliability, functionality, and quality of service. The objective of the seaweb experiments is to exercise telesonar modems in networked configurations where various modulation and networking algorithms can be assessed. In the long-term, the goal is to provide for a self-configuring network of distributed assets, with network links automatically adapting to the prevailing environment through selection of the optimum transmit parameters.

A full year of hardware improvements and in-air network testing helps ensure that the incremental developments tested at sea will provide tractable progress and mitigate overall developmental risk. In particular, DADS relies on the annual seaweb engineering experiments to push telesonar technology for undersea wireless networking. After the annual seaweb experiment yields a stable level of functionality, the firmware product can be further exercised, and refinements can be instituted during DADS system testing and by spin-off applications throughout the year. For example, in year 2001, seaweb technology enables the March–June *FRONT-3* ocean observatory on the continental shelf east of Long Island, NY [25]. These applications afford valuable long-term performance data that are not obtainable during seaweb experiments when algorithms are in flux and deployed modems are receiving frequent firmware upgrades.

The *Seaweb '98*, *'99*, and *2000* operating area in Buzzards Bay is framed in Figure 4. An expanse of 5- to 15-m shallow water is available for large-area network coverage with convenient line-of-sight radio access to Datasonics and Benthos facilities in western Cape Cod, MA. A shipping channel extending from the Bourne Canal provides episodes of high shipping noise useful for stressing the link signal-to-noise ratio (SNR) margins. The seafloor is patchy with regions of sand, gravel, boulders, and exposed granite.

Figure 5 shows *Seaweb '98*, *'99*, and *2000* modem rigging. Experiments occur during August and September when weather is conducive to regular servicing of deployed network nodes.

A representative sound-speed profile inferred from a conductivity-temperature-depth (CTD) probe during *Seaweb '98* is shown in Figure 6. For observed August and September sound-speed profiles, ray tracing suggests maximum direct-path propagation to ranges less than 1000 m, as Figure 7 shows. Beyond this distance, received acoustic energy is via boundary forward scattering. Ray tracing further indicates that received signal energy at significant ranges is attributable

FIGURE 4. The test site for *Seaweb '98*, *'99*, and *2000* is northern Buzzards Bay, MA. Water depth is 5 to 15 m.

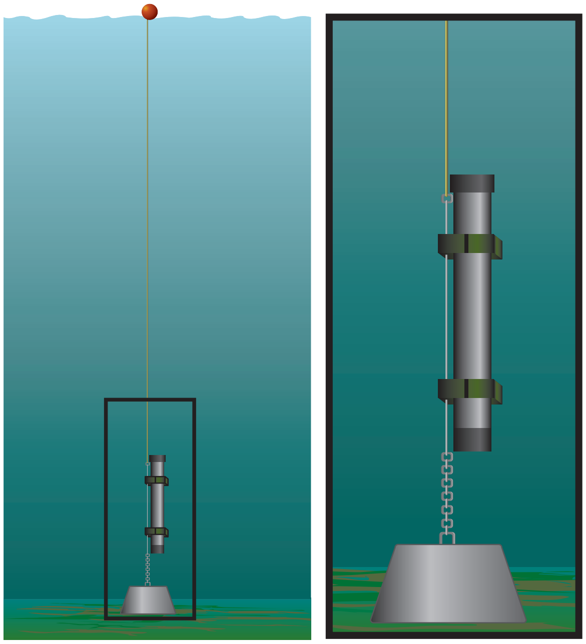

FIGURE 5. *Seaweb '98*, *'99*, and *2000* modems are deployed in Buzzards Bay with concrete weight, riser line, and surface float. The shallow water and simple rigging permit a small craft to rapidly service the network. Servicing includes battery replacement and modem firmware downloads.

to a very small near-horizontal continuum of projector elevation launch angles. Figure 8 presents predicted impulse responses for 10 ranges, each revealing multipath spreads of about 10 ms [26]. All ranges are considered "long" with respect to water depth. Summer afternoon winds and boat traffic regularly roughen the sea surface, increasing scattering loss and elevating noise levels.

***SEAWEB '98* EXPERIMENT**

Seaweb '98 led off a series of annual ocean experiments intended to progressively advance the state of the art for asynchronous, non-centralized networking. *Seaweb '98* used the Datasonics ATM875 second-generation telesonar modem [27] recently available as the product of a Navy SBIR Phase-2 contract.

The ATM875 normally uses 5 kHz of acoustic bandwidth with 120 discrete multiple-frequency shift keying (MFSK) bins configured to carry six Hadamard codewords of 20 tones each. Interleaving the codewords across the band increases immunity to frequency-selective fading, and Hadamard coding yields a frequency diversity factor of 5 for adverse channels having low or modest spectral coherence. This standard ATM875 modulation naturally supports three interleaved FDMA sets of 40 MFSK tonals and two codewords each. To further reduce multi-access interference (MAI) between sets, half the available bandwidth capacity provided additional guardbands during *Seaweb '98*. Thus, only 20 MFSK tonals composing one Hadamard codeword formed each FDMA set. The *Seaweb '98* installation was three geographic clusters of nodes with FDMA sets "A" through "C" mapped by cluster. For example, all nodes in cluster A were assigned the same FDMA carrier set for reception. Each cluster contained a commercial oceanographic sensor at a leaf node asynchronously introducing data packets into the network. This FDMA architecture was an effective multi-access strategy permitting simultaneous network activity in all three clusters without MAI [28]. A drawback of FDMA signaling is the inefficient use of available bandwidth. *Seaweb '98* testing was based on a conservative 300-bit/s modulation to yield a net FDMA bit-rate of just 50 bit/s. This was an acceptable rate since the *Seaweb '98* objective was to explore networking concepts without excessive attention to signaling issues. Within a cluster, TDMA was the general rule broken only by deliberate intrusion from the command center.

The gateway node is an experimental Navy racom buoy (Figure 9). The "master" node was installed approximately 1500 m from the gateway node. Gateway and master nodes formed cluster C, and so received and demodulated only the FDMA carriers of set C. Exercising the link between gateway and master nodes during various multi-hour and multi-day

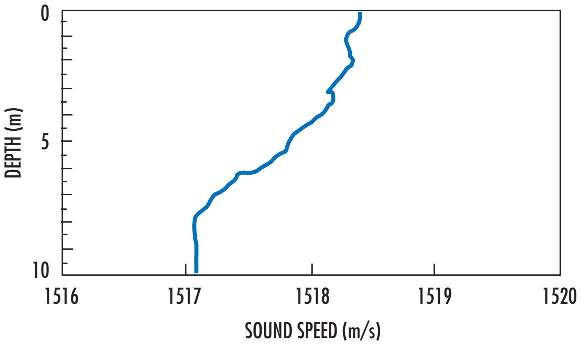

FIGURE 6. Sound-speed profiles calculated from conductivity and temperature probes are generally downward refracting during August–September at the *Seaweb'98*, *'99*, and *2000* site. This sound-speed profile, 1 of 14 obtained during *Seaweb '98*, is typical. The sound-speed gradient evident here is caused by summertime sea-surface warming.

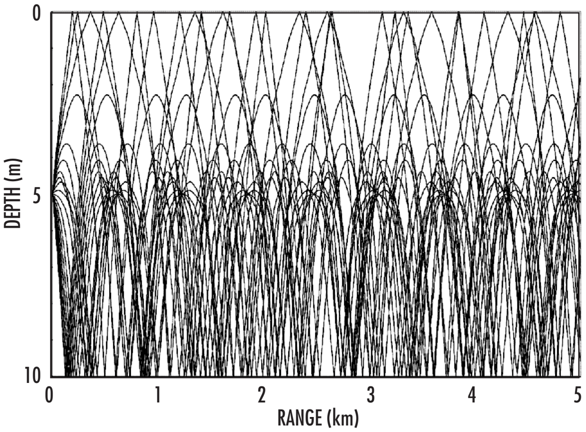

FIGURE 7. *Seaweb '98* propagation refracts downward in response to the vertical sound-speed gradient observed in Figure 6. Rays traced from a ±2.5° vertical fan of launch elevation angles model the telesonar sound channel for transmitter at 5-m depth. A parametric modeling study assessing the dependence of modem depth for this environment confirmed the general rule that long-range signaling in downward-refracting, non-ducted waters is optimized with modems placed nearer the seafloor. Hence, *Seaweb '98*, *'99*, and *2000* modem transducers are generally about 2 m above the bottom.

periods yielded link statistics for improving the wake-up and synchronization schemes in the modem receiver acquisition stage. This point-to-point testing identified specific suspected problems in the fledgling ATM875 implementation, and firmware modifications improved the success of packet acquisition from 80% to 97%.

Installation of a three-node subset of cluster A added a relay branch around Scraggy Neck, a peninsula protruding into Buzzards Bay. An Ocean Sensors CTD produced data packets relayed via each of the intervening A nodes to the master node, and then on to the gateway node. Each relay link was about 1500 m in range. Direct addressing of cluster-A nodes from the gateway node confirmed the existence of reliable links to all but the outermost node. Remarkably, a reliable link existed between two nodes separated by 3.6 km in spite of shoaling to 1 to 2 m in intervening waters! Various network interference situations were intentionally and unintentionally staged and tested until this simple but unprecedented relay geometry was well understood.

These early tests realized an unexpected benefit of the gateway link between the racom buoy and the radio-equipped workboat. End-to-end functionality of a newly installed node could be immediately verified. Field personnel would use a deck unit and the gateway node to test the network circuit that included the new modem as an intermediate node, or they would bidirectionally address the new modem via just the gateway route. Effectively, the workboat was a mobile node in the network equipped with both telesonar and gateway connections.

At this point, associates from the National Oceanic and Atmospheric Agency (NOAA) and Naval Surface Warfare Center (NSWC) visited *Seaweb '98*. A boat delivered them far into Buzzards Bay, where a hydrophone (deployed over the side with a telesonar deck unit) turned

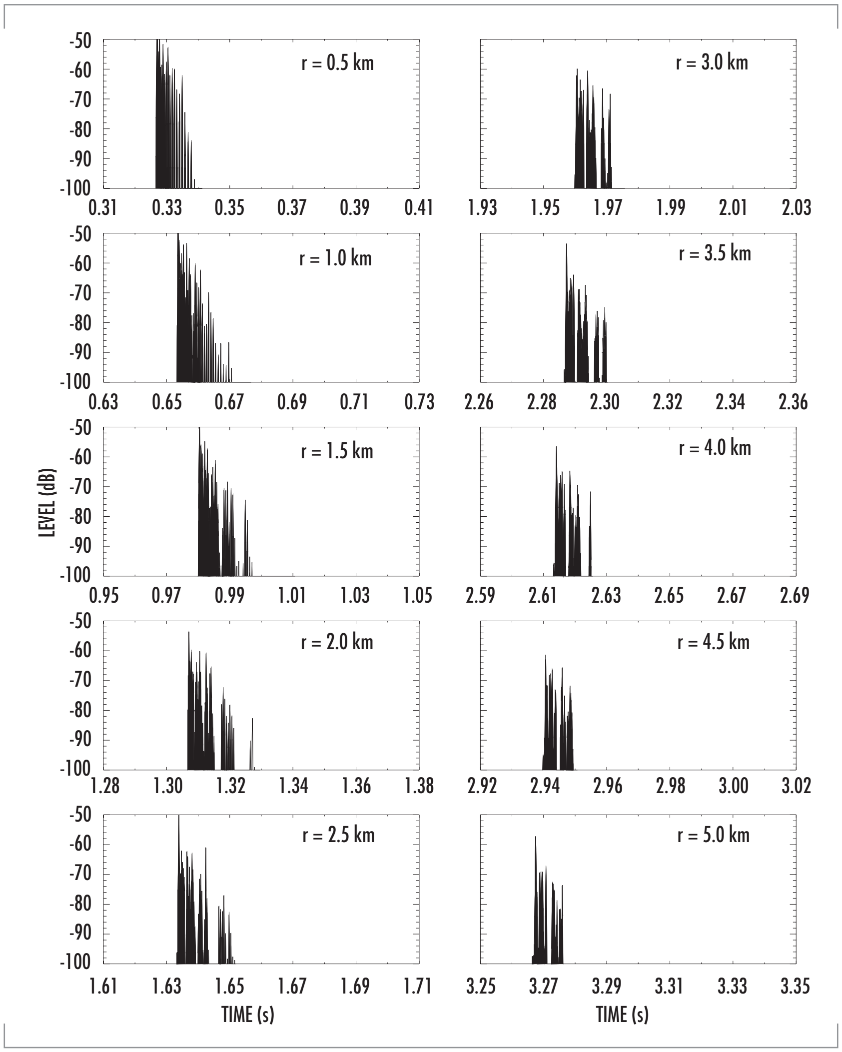

FIGURE 8. For a 10-m deep *Seaweb '99* channel, a 2-D Gaussian beam model predicts impulse responses for receivers located at 10 ranges, r. Response levels are in decibels referenced to a 0-dB source. Multipath spread is about 10 ms. Note the *Seaweb '98*, *'99*, and *2000* working ranges are hundreds of times greater than the water depths, and boundary interactions are therefore complex. For rough sea floor and sea surface, the 2-D model approximation must give way to 3-D forward scattering, and the predicted response structures will instead be smeared by out-of-plane propagation. *Seaweb 2000* testing includes channel probes designed to directly measure channel scattering functions with receptions recorded at various ranges by telesonar test beds. These channel measurements support analysis of experimental signaling and help calibrate an experimental 3-D Gaussian beam model under development for telesonar shallow-water performance prediction.

the boat into just such a mobile network node. The visitors typed messages, which were relayed through the network and answered by personnel at the ashore command center.

Next, a branch was added to cluster A with a Falmouth Scientific 3-D current meter and CTD. Network contention was studied by having the two cluster-A sensor nodes generate packets at different periods such that network collisions would occur at regular intervals with intervening periods of non-colliding network activity.

Finally, cluster B was introduced to the network with internode separations of 2 km. A third device generated data packets. With all available network nodes installed and functioning, the remaining few days involved a combination of gradually arranging network nodes with greater spacing as charted in Figure 10, and of doing specialized signal testing with the telesonar test bed [29]. In addition, the telesonar test bed was deployed in the center of the network for five data-acquisition missions and recorded 26 hours of acoustic network activity. The test bed also included a modem, permitting it to act as the tenth network node and giving ashore operators the ability to remotely control and monitor test-bed operations. The test-bed node provides raw acoustic data for correlation with automatic modem diagnostics, providing opportunity to study failure modes using recorded time series.

Seaweb '98 demonstrated the feasibility of low-cost distributed networks for wide-area coverage. During 3 weeks of testing in September, the network performed reliably through a variety of weather and noise events. Individual network links spanned horizontal ranges hundreds of water depths in length. The *Seaweb '98* network connected widely spaced autonomous modems in a binary-tree topology with a master node at the base and various oceanographic instruments at outlying leaf nodes. Also connected to the master node was an acoustic link to a gateway buoy, providing a line-of-sight digital radio link to the command center ashore. The network transported data packets acquired by the oceanographic instruments through the network to the master node, on to the gateway node, and then to the command center. The oceanographic instruments and modems generally operated according to preprogrammed schedules designed to periodically produce network collisions, and personnel at the command center or aboard ship also remotely controlled network nodes in an asynchronous manner.

The most significant result of *Seaweb '98* is the consistent high quality of received data obtained from

FIGURE 9. In *Seawebs '98*, *'99*, and *2000*, a radio/acoustic communications (racom) buoy provides a very reliable line-of-sight packet-radio link to seaweb servers at the shore command center and on the work boat. The radio link is a 900-MHz spread-spectrum technology commercially known as Freewave. In *Seawebs '99* and *2000*, additional gateway nodes using cellular modems linked via Bell Atlantic and the Internet provide even greater flexibility and provide access by seaweb servers at various locales across the country.

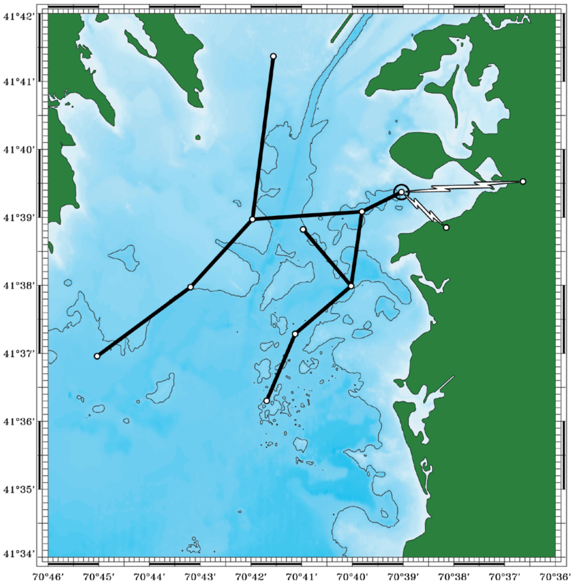

FIGURE 10. *Seaweb '98* demonstrated store and forward of data packets from remote commercial sensors including a CTD, a current vector meter, and a tilt/heading sensor (at the most northerly, westerly, and southerly leaf nodes, respectively) via multiple network links to the racom gateway buoy (large circle). Data packets are then transmitted to the ashore command center via line-of-sight packet radio. An FDMA network with three frequency sets reduced the possibility of packet collisions. Following extensive firmware developments supported by this field testing, the depicted topology was exercised during the final days of the experiment. Isobaths are contoured at 5-m intervals.

remote autonomous sensors. Data packets arrived at the command center via up to four acoustic relays and one RF relay. About 2% of the packets contained major bit-errors attributable to intentional collisions at the master node. The quality of data was very high even after the network was geographically expanded. Reliable direct telesonar communications from the gateway node to a node nearly 7 km distant suggested the network could be expanded considerably more, in spite of the non-ducted 10-m deep channel. The *Seaweb '98* environment could have supported 4-km links using the same ATM875 modems and omnidirectional transducers. Attesting to the channel-tolerant nature of the MFSK modulation, an early phase of testing maintained a 3-km link between two nodes separated by a 1- to 2-m deep rocky shoal. Consistent network degradation occurred during most afternoons and is attributable to summer winds roughening the sea-surface boundary and thus scattering incident acoustic energy. Automated network operations continued during heavy rains and during ship transits through the field.

Seaweb '98 demonstrated the following network concepts: (1) store and forward of data packets; (2) transmit retries and automatic repeat request; (3) packet routing; and (4) cell-like FDMA node grouping to minimize MAI between cells. In addition, the following DADS concepts were demonstrated: (1) networked sensors; (2) wide-area coverage; (3) racom gateway; (4) robustness to shallow-water environment; (5) robustness to shipping noise; (6) low-power node operation with sleep modes; (7) affordability; and (8) remote control. Finally, *Seaweb '98* resulted in dramatic improvements to the ATM875 modem and improved its commercial viability for non-networked applications.

Seaweb '98 observations underscore the differences between acoustic networks and conventional networks. Limited power, low bandwidth, and long propagation times dictate that seaweb networks be simple and efficient. Data compression, forward error correction, and data filtering must be employed at the higher network levels to minimize packet sizes and retransmissions. At the network layer, careful selection of routing is required to minimize transmit energy, latency, and net energy consumption, and to maximize reliability and security. At the physical and MAC layers, adaptive modulation and power control are the keys to maximizing both channel capacity (bit/s) and channel efficiency (bit-km/joule).

SEAWEB '99 EXPERIMENT

Seaweb '99 continued the annual series of telesonar experiments incrementally advancing the state of the art for undersea wireless networks. During a 6-week period, up to 15 telesonar nodes operated in various network configurations in the 5- to 15-m waters of Buzzards Bay. Network topologies provided compound multi-link routes. All links used a rudimentary form of the telesonar handshake protocol featuring an adaptive power-control technique for achieving sufficient but not excessive SNR at the receiver. Handshaking provided the means for resolving packet collisions automatically using retries from the transmitter or automatic-repeat-request (ARQ) packets from the receiver.

The multi-access strategy was a variation of FDMA wherein the six available 20-tone Hadamard words provided six separate FDMA sets, A through F. Rather than clustering the FDMA sets as in *Seaweb '98*, the notion here was to optimally assign FDMA receiver frequencies to the various nodes in an attempt to minimize collisions through spatial separation and the corresponding transmission loss. This approach represents an important step toward network self-configuration and prefigures the future incorporation of secure CDMA spread-spectrum codes to be uniquely assigned to member nodes during the initialization process.

Node-to-node ranging employed a new implementation of a round-trip-travel time measurement algorithm with 0.1-ms resolution linked to the DSP clock rate. Range estimation simply assuming a constant 1500 m/s sound speed was consistently within 5% of GPS-based measurements for all distances and node pairs.

A significant development was the introduction of the seaweb server. It interprets, formats, and routes downlink traffic destined for undersea nodes. On the uplink, it archives information produced by the network, retrieves the information for an operator, and provides database access for client users. The server manages seaweb gateways and member nodes. It monitors, displays, and logs the network status. The server manages the network routing tables and neighbor tables and ensures network interoperability. *Seaweb '99* modem firmware permitted the server to remotely reconfigure routing topologies, a foreshadowing of future self-configuration and dynamic network control. The seaweb server is a graphical set of LabView virtual instruments implemented under Windows NT on a laptop PC. A need for the server was illustrated when operators bypassed server oversight and inadvertently produced a circular routing where a trio of nodes continuously passed a packet between themselves until battery depletion finally silenced the infinite loop.

In *Seaweb '99,* the server simultaneously linked with a Bell Atlantic cellular digital packet data (CDPD) gateway node via the Internet and with the packet-radio racom gateway link via a serial port. A milestone was the establishment of a gateway-to-gateway route through the seaweb server that was exercised automatically over a weekend.

Seaweb '99 included an engineering test for the "Front-Resolving Observation Network with Telemetry" (FRONT) application, with large acoustic Doppler current profiler (ADCP) data packets synthesized and passed through the network with TDMA scheduling. A study of network capacity examined the periodic uplinking of data packets while asynchronously issuing server-generated downlink commands to poll sensors.

For every packet received by a *Seaweb '99* node, the modem appended link metrics such as bit-error rate (BER), automatic gain control (AGC), and SNR. These diagnostics aided post-mortem system analysis. Performance correlated strongly with environmental factors such as refraction, bathymetry, wind, and shipping, although no attempt was made to quantify these relationships in *Seaweb '99*.

The ATM875 second-generation telesonar modem again served as the workhorse modem for all network nodes. During the last phase of the experiment, progress was thwarted by memory limitations of the Texas Instruments TMS320C50 DSP. A firmware bug could not be adequately resolved because of lack of available code space for temporary in-line diagnostics. Consequently, the final days of the test reverted to a prior stable version of the *Seaweb '99* code and the 15-node network charted in Figure 11 covered a less ambitious area than originally intended. These limitations plus the desire to begin implementing FHSS and DSSS signaling motivated the initiation of ATM885 third-generation telesonar modem development for *Seaweb 2000*.

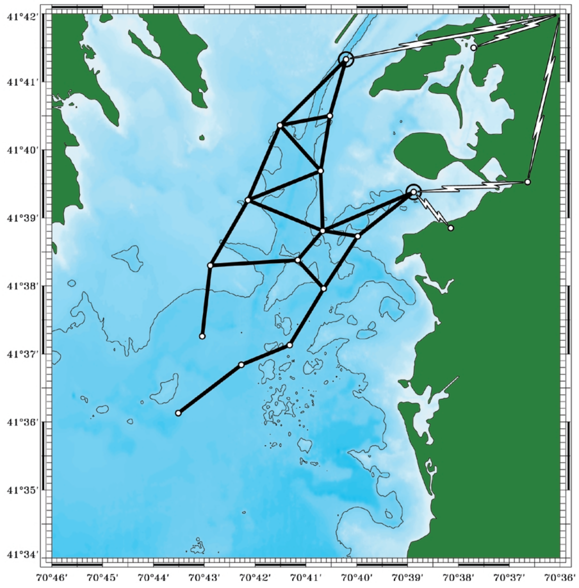

FIGURE 11. *Seaweb '99* explored the use of handshaking and power control. An ADCP sensor node, a tilt/heading sensor node, and a CTD sensor node generated data packets, and the network routed them through various paths. The racom gateway node (easterly large circle) again provided a solid link to shore. A second gateway node (northerly large circle) installed on a Coast Guard caisson near the Bourne canal provided a Bell Atlantic cellular modem link to the Internet and then to the command center. The Seaweb server running on a laptop PC managed both gateway connections and archived all network activity.

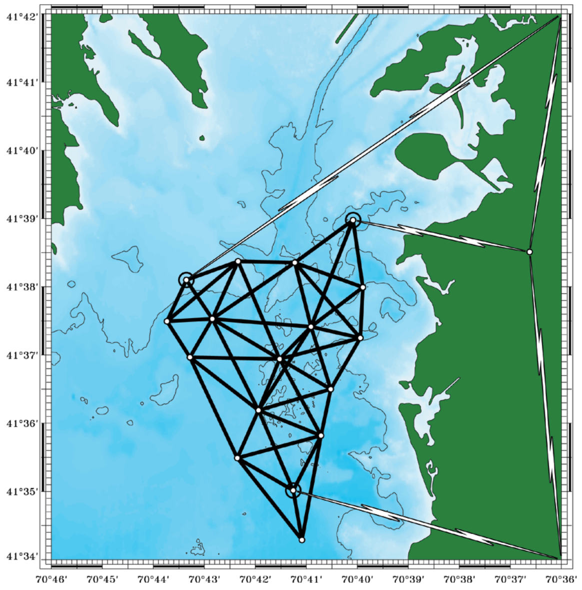

FIGURE 12. *Seaweb 2000* exercised the telesonar handshake protocol in a network context. The 17-node seaweb network delivered oceanographic data from sensor nodes to gateway nodes—one with line-of-sight packet radio and two with cellular telephone modems. During the final week, a seaweb super server operating at the Oceans 2000 Conference in Providence, RI, administered *Seaweb 2000* via the Internet.

SEAWEB 2000 EXPERIMENT

The *Seaweb 2000* network included up to 17 nodes, with one of the fully connected configurations charted in Figure 12. This experiment achieved major advances in both hardware and firmware.

Use of the ATM875 modem during *Seawebs '98* and *'99* continually thwarted progress in firmware development because of limited memory and processing speed. The ATM885 modem shown in Figure 13 overcomes these shortcomings with the incorporation of a more powerful DSP and additional memory. Now, telesonar firmware formerly encoded by necessity as efficient machine language is reprogrammed on the ATM885 as a more structured set of algorithms. The *ForeFRONT-1* (November 1999), *FRONT-1* (December 1999), *ForeFRONT-2* (April 2000), *Sublink 2000* (May 2000), and *FRONT-2* (June 2000) experiments hastened the successful transition of *Seaweb '99* firmware from the ATM875 to the ATM885. These intervening seaweb applications were stepping stones toward achieving basic ATM885 hardware readiness prior to instituting *Seaweb 2000* upgrades.

Seaweb 2000 implements in firmware the core features of a compact, structured protocol. The protocol efficiently maps network-layer and MAC-layer functionality onto a physical layer based on channel-tolerant, 64-bit utility packets and channel-adaptive, arbitrary-length data packets. Seven utility packet types are implemented for *Seaweb 2000*. These packet types permit data transfers and node-to-node ranging. A richer set of available utility packets is being investigated with OPNET simulations, but the seven core utility packets provide substantial networking capability.

The initial handshake consists of the transmitter sending an RTS packet and the receiver replying with a CTS packet. This roundtrip establishes the communications link and probes the channel to gauge optimal transmit power. Future enhancements to the protocol will support a choice of data modulation methods, with selection based on channel estimates derived from the RTS role as a probe signal. A "busy" packet is issued in response to an RTS when the receiver node decides to defer data reception in favor of other traffic. Following a successful RTS/CTS handshake, the data packet(s) are sent. The *Seaweb 2000* core protocol provides for acknowledgments, either positive or negative, of a data message. The choice of acknowledgment type will depend on the traffic patterns associated with a particular network mission. *Seaweb 2000* explored the factors that will guide this application-specific choice.

A "ping" utility packet initiates node-to-node and node-to-multinode identification and ranging. An "echo" packet is the usual response to a received ping.

In *Seaweb 2000*, FDMA architectures are superseded by hybrid CDMA/TDMA methods for avoiding mutual interference. FDMA methods sacrifice precious bandwidth and prolong the duration of a transmission, often aggravating MAI rather than resisting it. Furthermore, the use of a small number of frequency sets is viewed as an overly restrictive networking solution. Although these drawbacks were expected, *Seawebs '98* and *'99* employed FDMA primarily for ease of implementation as a simple extension to the rigid ATM875 telesonar machine code. The ATM885 permits a break from those restrictions.

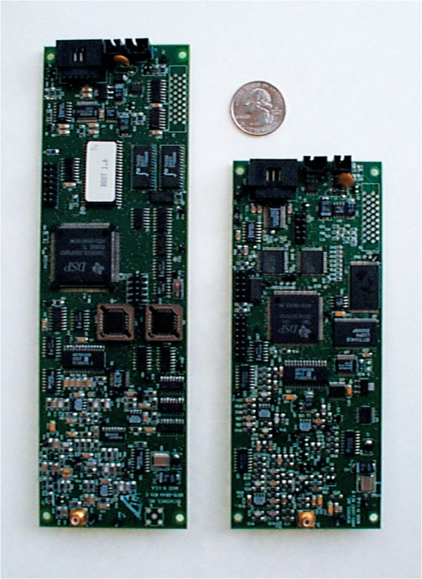

FIGURE 13. The TMS320C5410-based ATM885 telesonar modem debuted in *Seaweb 2000* with a four-fold increase in memory and processing speed over the TMS320C50-based ATM875. This hardware upgrade reduced battery-energy consumption and overcame firmware-development limitations experienced in *Seaweb '99*. The ATM885 supports 100 million instructions per second (MIPS) and 320K words of memory compared with 25 MIPS and 74K available from the ATM875.

Seaweb 2000 execution fully incorporates the experimental approach tried in *Seaweb '99* of establishing two parallel networks—one in air at the command center and one in the waters of Buzzards Bay. This approach minimizes time-consuming field upgrades by providing a convenient network for troubleshooting deployed firmware and testing code changes prior to at-sea downloads.

As a further analysis aid, all modems now include a data-logging feature. All output generated by the ATM885 and normally available via direct serial connection is logged to an internal buffer. Thus, the behavior of autonomous nodes can be studied in great detail after recovery from the sea. To take maximum advantage of this capability, *Seaweb 2000* code includes additional diagnostics related to channel estimation (e.g., SNR, multipath spread, Doppler spread, range rate, etc.), demodulation statistics (e.g., BER, AGC, intermediate decoding results, power level, etc.), and networking (e.g., data packet source, data packet sink, routing path, etc.). For seaweb applications, the data-logging feature can also support the archiving of data until such time that an adjacent node is able to download the data. For example, a designated sink node operating without access to a gateway node can collect all packets forwarded from the network and telemeter them to a command center when interrogated by a gateway (such as a ship arriving on station for just such a data download).

Increasing the value of diagnostic data, the C5410 real-time clock is maintained even during sleep state. Although this clock may not have the stability required for certain future network applications, its availability permits initial development of in-water clock-synchronization techniques.

The new ATM885 modem also includes a provision for a watchdog function hosted aboard a microchip independent of the C5410 DSP. The watchdog resets the C5410 DSP upon detection of supply voltage drops or upon cessation of DSP activity pulses. The watchdog provides a high level of fault tolerance and permits experimental modems to continue functioning in spite of system errors. A watchdog reset triggers the logging of additional diagnostics for thorough troubleshooting after modem recovery.

An aggressive development schedule following *Seaweb '99* and preceding *Seaweb 2000* matured the seaweb server as a graphical user interface with improved reliability and functionality consistent with *Seaweb 2000* upgrades.

Recent telesonar engineering tests have played host to an applied research effort known as SignalEx [30]. This research uses the telesonar test beds to record high-fidelity acoustic receptions and measure relative performance for numerous signaling methods. *Seaweb 2000* hosted SignalEx testing during the second week of testing. The advantage of coupling SignalEx research with seaweb engineering is that both activities benefit—SignalEx gains resources and seaweb gains added empirical test control. By the fifth week, the major *Seaweb 2000* engineering developments reached a level of stability permitting experimental use of acoustic navigation methods for node localization, cost functions for optimized network routing, and statistics gathering for network traffic analysis.

In summary, the specific implementation objectives of *Seaweb 2000* are (1) packet forwarding through network, under control of remotely configurable routing table; (2) 64-bit header; (3) improved software interface between network layer and modem processing; (4) improved wake-up processing, i.e., detection of 2-of-3 or 3-of-4 tones, rather than 3-of-3; (5) improved acquisition signal, i.e., one long chirp, rather than three short chirps; (6) improved channel-estimation diagnostics; (7) logging of channel estimates; (8) RTS/CTS handshaking; (9) configurable enabling of RTS/CTS handshake; (10) power control; (11) watchdog; (12) ARQ; (13) packet time-stamping; and (14) a simple form of adaptive modulation restricted solely to parameter selection for Hadamard MFSK modulation.

The new ATM885 hardware and the *Seaweb 2000* protocols are major strides toward the ultimate goal of a self-configuring, wireless network of autonomous undersea devices.

CONCLUSION

Telesonar is an emerging technology for wireless digital communications in the undersea environment. Telesonar transmission channels include shallow-water environments with node-to-node separations hundreds of times greater than the water depth. Robust, environmentally adaptive acoustic links interconnect undersea assets, integrating them as a unified resource.

Seaweb offers a blueprint for telesonar network infrastructure. Warfare considerations stipulate that the network architecture will support rapid installation, wide-area coverage, long standoff range, invulnerability, and cross-mission interoperability. Seaweb is an information system compatible with low bandwidth, high latency, and variable quality of service. Seaweb connectivity emphasizes reliability, flexibility, affordability, energy efficiency, and transmission security. Network interfaces to manned command centers via gateway nodes such as the racom buoy are an essential aspect of the seaweb concept. C^3N via seaweb supports common situational awareness and collective adaptation to evolving rules of engagement. Seaweb revolutionizes naval warfare by ultimately extending network-centric operations into the undersea battlespace.

The *Seaweb '98*, *'99*, and *2000* experiments incrementally advanced telesonar underwater acoustic signaling and ranging technology for undersea wireless networks. The constraints imposed by acoustic transmission through shallow-water channels have yielded channel-tolerant signaling methods, hybrid multi-user access strategies, novel network topologies, half-duplex handshake protocols, and iterative power-control techniques. *Seawebs '98* and *'99*, respectively, included 10 and 15 battery-powered, anchored telesonar nodes organized as non-centralized, bidirectional networks. These tests demonstrated the feasibility of battery-powered, wide-area undersea networks linked via radio gateway buoy to the terrestrial internet. Testing involved delivery of remotely sensed data from the sea and remote control from manned command centers ashore and afloat. *Seaweb 2000* included 17 nodes equipped with new telesonar modem hardware. It introduced a compact protocol anticipating adaptive network development.

In late summer, *Seaweb 2001* will be conducted in a large expanse of 30- to 300-m waters adjacent to San Diego, CA. The annual seaweb experiments will continue to extend area coverage, resource optimization, network capacity, functionality, and quality of service. Active research includes spread-spectrum signaling, directional transducers [31], *in situ* channel estimation, adaptive modulation, *ad hoc* network initialization, and node ranging and localization.

SSC San Diego is applying seaweb technology for ocean surveillance (DADS Demonstration Project), littoral ASW (Hydra Project), oceanographic research (FRONT Project), submarine communications (Sublink Project) and UUV command and control (SLOCUM and EMATT). Additional applications are proposed.

Deployable autonomous undersea systems will enhance the warfighting effectiveness of submarines, maritime patrol aircraft, amphibious forces, battle groups, and space satellites. Wide-area sensor grids, leave-behind multistatic sonar sources, mine-hunting robots, swimmer-delivery systems, and autonomous vehicles are just a few of the battery-powered, offboard devices that will augment high-value space and naval platforms. Distributed system architectures offer maximum flexibility for addressing a wide array of ocean environments and military missions.

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