TITLE: Telesonar Signaling and Seaweb Underwater Wireless Networks

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Telesonar Signaling and Seaweb Underwater Wireless Networks

J. A. Rice
Space and Naval Warfare Systems Center, San Diego
Acoustics Branch, Code D857
San Diego, CA 92152
United States
rice@spawar.navy.mil

Abstract— **Seawebs '98, '99, and 2000 are experiments incrementally advancing 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 bi-directional 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 introduces new telesonar modem hardware and a compact protocol for advanced network development. Sublinks '98, '99, and 2000 are parallel experiments that extend Seaweb networking to include a submerged submarine as a mobile gateway node.**

I. 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 [3,4] and later identified as the first-generation *telesonar* modem. To promote further development, the U.S. invested small business innovative research (SBIR) funding and Navy laboratory support with expectations that energy-efficient, inexpensive telesonar modems would spawn undersea wireless networking methodologies embodied by the *Seaweb* concept [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 functionality implemented on commercial off-the-shelf (COTS) telesonar hardware shows enormous promise for numerous ocean applications.

Off-board 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).

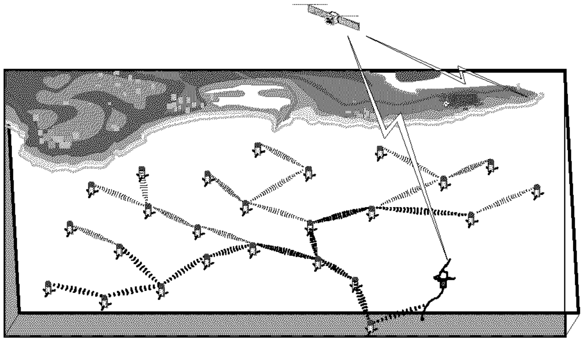

Fig. 1. Seaweb underwater acoustic networking provides digital wireless links enabling deployable autonomous distributed systems (DADS). Gateways to manned control centers include radio links to space or shore and telesonar links to ships.

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 depicted in Fig. 1. Future sensor nodes in a DADS network generate concise anti-submarine 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 on-board Seaweb server.

The DADS application generally involves operation in 50- to 300-m waters and node spacings of 1 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 characteristic (ROC) 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 geo-localization 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 the natural initial use of Seaweb technology because it forms a fixed cellular network grid of inexpensive interoperable nodes. This architecture is well suited for supporting autonomous oceanographic

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sampling network (AOSN) concepts [10] and various autonomous operations, including navigation, control, and telemetry of UUV mobile nodes.

II. CONCEPT OF OPERATIONS

Telesonar wireless acoustic links interconnect distributed undersea assets, 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 intelligent master nodes and various interfaces to manned command centers. It provides the command, control, and communications 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, sea mines, relay stations).

Seaweb *peripherals* include mobile nodes (*e.g.*, UUVs, including swimmers and crawlers) and specialized nodes (*e.g.*, bi-static 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 interface permitting satellites and maritime patrol aircraft to access submerged, autonomous systems. Similarly, submarines can access Seaweb with telesonar signaling in the WQC-2 underwater telephone band or by using other organic sonars. Seaweb provides the submarine commander several options for secure, digital connectivity at speed and depth, including bi-directional access to all Seaweb-linked resources and distant gateways.

A Seaweb *server* resides at manned command centers and is an interface to the undersea network as shown in Fig. 2. The server archives all incoming data packets and provides read-only access to client stations via internet. A single designated "super" server controls and reconfigures the network.

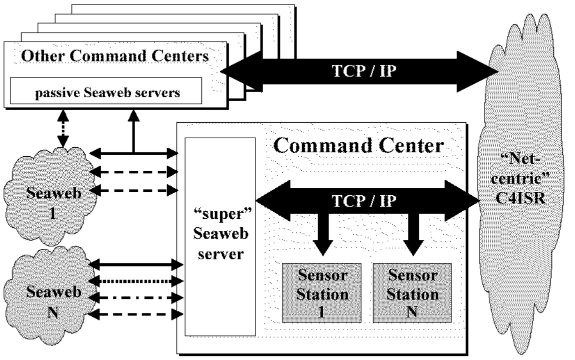


Fig. 2. Seaweb extends modern "net-centric" interconnectivity to the undersea realm. Wireless underwater networks include gateway nodes with radio, acoustic, wire, or fiber links to manned command centers where a Seaweb server provides the required user interface. Command centers may be aboard ship, 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 "super" Seaweb server manages and controls the undersea network. All Seaweb servers archive Seaweb packets and provide data access to client stations.

Seaweb quality of service is limited by low-bandwidth, half-duplex, high-latency telesonar links. Occasional outages from poor propagation or elevated noise levels can disrupt telesonar links [12]. Ultimately, the available energy supply dictates service life and battery-limited nodes must be energy conserving [13]. 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.

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

Simplicity, efficiency, reliability, and security are the governing design principles. Half-duplex handshaking [14] asynchronously establishes adaptive telesonar links [15] as described in Fig. 3. The initiating node transmits a request-to-send (RTS) waveform with a frequency-hopped, spread-spectrum (FHSS) [16] series or direct-sequence spread-spectrum (DSSS) [17] pseudo-random carrier uniquely addressing the intended receiver. (Alternatively, the initiating node may transmit a universal pattern for broadcasting or when establishing links with unknown nodes.) The addressed node detects the request and awakens from a low-power sleep state to demodulate. Further processing of the request signal provides an estimate of the channel scattering function and signal excess. The addressed node then

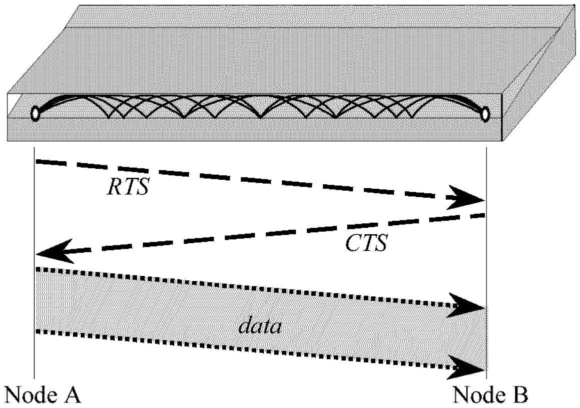


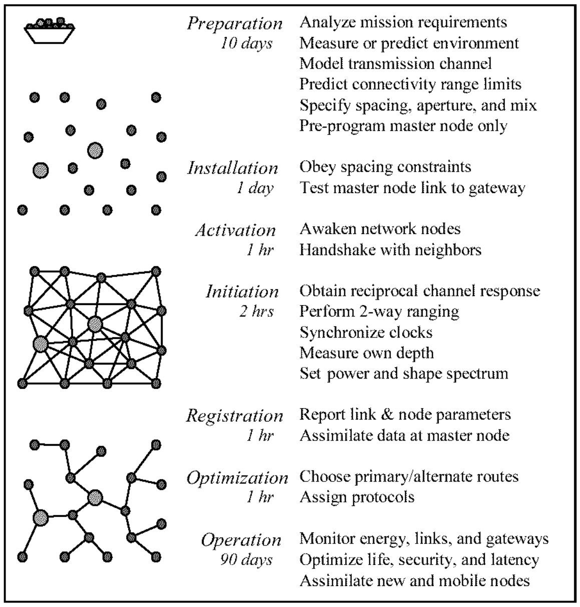
Fig. 3. Seaweb handshake protocol for data transfer involves Node A initiating a request-to-send (RTS) modulated with a channel-tolerant, spread-spectrum pattern uniquely associated with intended receiver Node B. So addressed, Node B awakens and demodulates the fixed-length RTS packet. Node B estimates 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) exchange.

acknowledges receipt with a FHSS or DSSS acoustic reply. 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.

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 communications techniques to exploit the unique aspects of the underwater channel. Directional transducers further enhance the performance of these devices [18].

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 [19], with provision for bi-directional asymmetry.

Spread-spectrum modulation is consistent with the desire for asynchronous multiple-access to the physical channel using code-division multiple-access (CDMA) networking [20]. Nevertheless, the Seaweb concept does not exclude time-division multiple-access (TDMA) or frequency-division multiple-access (FDMA) methods and is in fact 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.



Preparation *10 days*	Analyze mission requirements Measure or predict environment Model transmission channel Predict connectivity range limits Specify spacing, aperture, and mix Pre-program master node only
Installation *1 day*	Obey spacing constraints Test master node link to gateway
Activation *1 hr*	Awaken network nodes Handshake with neighbors
Initiation *2 hrs*	Obtain reciprocal channel response Perform 2-way ranging Synchronize clocks Measure own depth Set power and shape spectrum
Registration *1 hr*	Report link & node parameters Assimilate data at master node
Optimization *1 hr*	Choose primary/alternate routes Assign protocols
Operation *90 days*	Monitor energy, links, and gateways Optimize life, security, and latency Assimilate new and mobile nodes

Fig. 4. An automatic process of self-organization follows an ad hoc deployment of telesonar nodes. These methods are tested as OPNET simulations and incrementally implemented in Seaweb experiments.

Optimized network topologies are configured and maintained under the supervision of master nodes [21] as outlined in Fig. 4. 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 features support initialization, navigation, and network optimization.

III. DEVELOPMENTAL APPROACH

Given the DADS performance requirements, Seaweb research is advancing telesonar modem technology for reliable underwater signaling by addressing the issues of (a) adverse transmission channel; (b) asynchronous networking; (c) battery-energy efficiency; (d) transmission security; and (e) cost.

Despite an architectural philosophy emphasizing simplicity, Seaweb is a complex system and its development is a grand challenge. Given the high cost of sea testing and the need for many prototype nodes, the natural course is to perform 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 exploration of candidate Seaweb architectures and refinement of networking protocols [22]. Meanwhile, controlled experimentation in actual ocean conditions incrementally advances telesonar signaling technology [23].

Seaweb development applies the results from these research activities with a concentration of resources in prolonged ocean experiments. These annual Seaweb experiments are designed to validate system analysis and purposefully evolve critical technology areas such that the Seaweb state-of-the-art makes an advance toward greater reliability and functionality. The objective of the Seaweb experiments is to implement and test telesonar modems in networked configurations where various modulation and networking algorithms can be exercised, compared, and conclusions drawn. 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 to 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 instituted during DADS system testing and by spin-off applications throughout the year. For example, in year 2000, Seaweb technology was implemented in the May Sublink 2000 and in the April ForeFRONT-2 and June FRONT-2 experiments [24]. These applications afford valuable long-term performance data that are not obtainable during Seaweb's aggressive engineering activities when algorithms are in flux and deployed modems are receiving frequent firmware upgrades.

The Seaweb '98, '99, and 2000 operating area is the readily accessible waters of Buzzards Bay, MA, framed in Fig. 5. An expanse of 5- to 15-meter shallow water is available for large-area network coverage with convenient line-of-sight radio contact to Datasonics and Benthos facilities in western Cape Cod. A shipping channel extending from the Bourne Canal provides periodic 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.

Seaweb '98, '99, and 2000 modem rigging is illustrated in Fig. 6. Testing is performed 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 plotted in Fig. 7. For observed August and September sound-speed profiles, ray tracing suggests maximum direct-path propagation to ranges less than 1000 m as seen in Fig. 8. Beyond this distance, received acoustic energy is via boundary forward scattering. Ray tracing further indicates that received signal energy at significant ranges is attributable to a very small near-horizontal continuum of projector elevation launch angles. Fig. 9 presents predicted impulse responses for 10 ranges each revealing multipath spreads of about 10 ms [25]. 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.

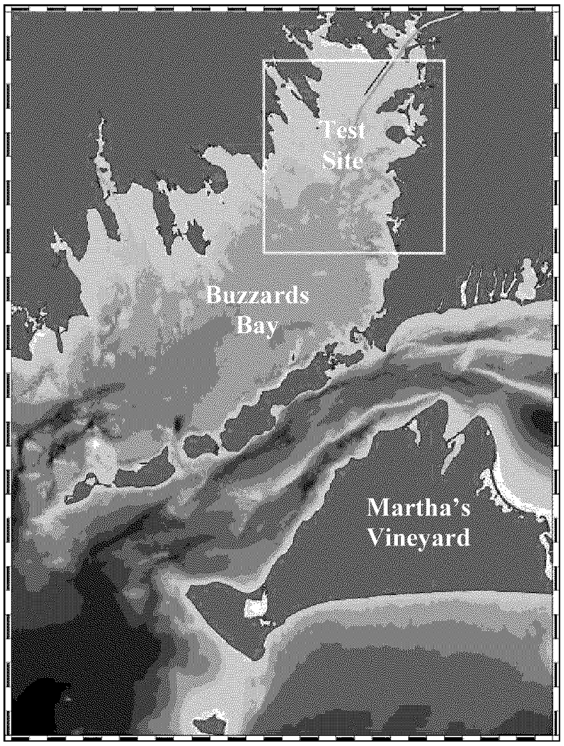


Fig. 5. The test site for Seawebs '98, '99 and 2000 is northern Buzzards Bay, MA. Water depth is 5 to 15 m.

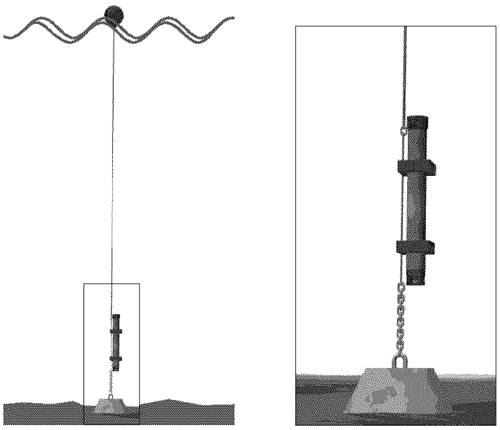


Fig. 6. Seaweb '98, '99, and 2000 modems are deployed in Buzzards Bay with concrete weight, riser line, and surface float. The shallow water and simple rigging permit a small craft to rapidly service the network, including battery replacement and firmware downloads.

IV. TBED '96

A Seaweb predecessor called "telemetry buoy environmental data" (TBED) involved a brute-force networking approach using unmodified COTS Datasonics ATM850 modems. The ATM850 is one of the earliest DSP-based modems, and hence is identified as the "first-generation" telesonar modem. TBED networking used the ATM850's M-ary frequency-shift-keying (MFSK) modulation in a TDMA format wherein all member nodes would sequentially report a compete matrix of data for up to three environmental sensors per node. TBED was significant in that it was the first undersea acoustic digital network with a non-centralized architecture. That is, the network did not involve a central master node with direct links to all slave nodes. Non-centralized architectures are a Seaweb hallmark because of network expandability and area coverage not constrained by point-to-point links. To achieve data forwarding, every TBED transmission was a broadcast including all data from all sensor nodes, thereby permitting receiving nodes to update any stale matrix elements for retransmission in their respective TDMA slots. Thus, the data would reliably but inefficiently be disseminated through the network, ultimately reaching a gateway node. The Navy successfully tested this concept with four nodes in the Gulf of Mexico in 1996. The tested TDMA format could accommodate up to 10 nodes.

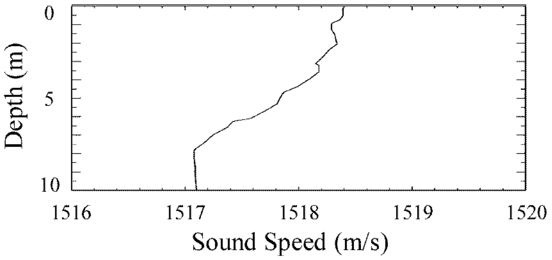


Fig. 7. Sound-speed profiles calculated from conductivity and temperature probes are generally downward refracting during August-September at the Seaweb '98, '99, and 2000 site. This sound-speed profile, 1 of 14 obtained during Seaweb '98, is typical.

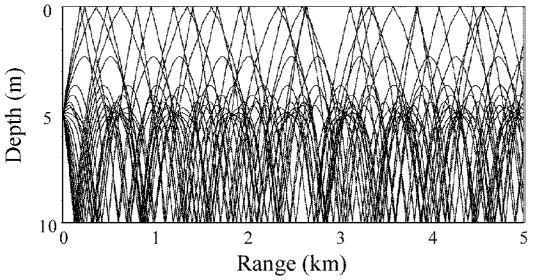


Fig. 8. Seaweb '98 propagation refracts downward in response to vertical sound-speed gradients caused by sea-surface warming. The sound channel is modeled above as rays traced from a ±2.5° fan of elevation angles launched from a transmitter at 5-m depth. A parametric modeling study assessing the dependence of modem depth for this environment confirmed the general rule that long-range signaling in downward-refracting, non-ducted waters is favored by modems placed nearer the seafloor. Hence, Seaweb '98, '99, and 2000 modem transducers are generally about 2 m above the bottom.

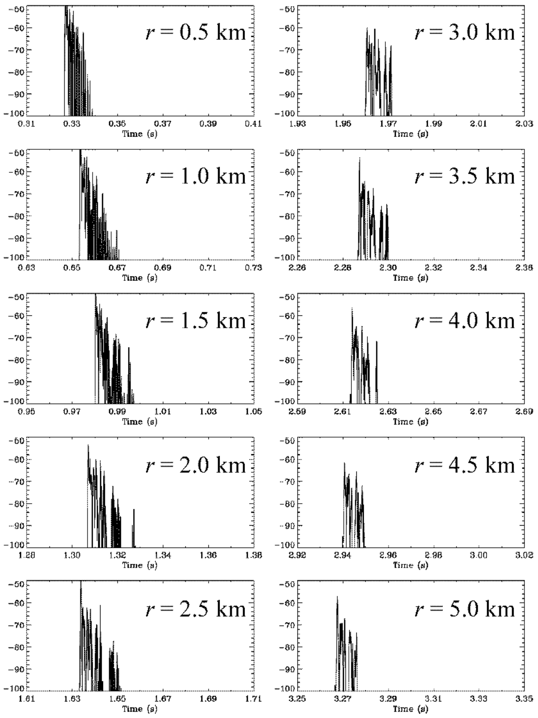


Fig. 9. For a 10-m deep Seaweb '99 channel, a 2-D Gaussian beam model predicts impulse responses for receivers located at 10 ranges, *r*. Response levels are in decibels referenced to a 0-dB source. Multipath spread is about 10 ms. Note the Seaweb '98, '99, and 2000 working ranges are hundreds of times greater than the water depths and boundary interactions are 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 testbeds. These channel measurements are used to calibrate an experimental 3-D Gaussian beam model under development for telesonar shallow-water performance prediction and to support analysis of experimental signaling.

V. SEAWEB '98

Seaweb '98 led off a continuing 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 [26] recently available as the product of a Navy SBIR Phase-2 contract.

The ATM875 normally uses 5 kHz of acoustic bandwidth with 120 discrete MFSK bins configured to carry 6 Hadamard codewords of 20 tones each. The codewords are interleaved to provide maximum resistance to frequency-selective fading and the Hadamard coding yields a frequency diversity factor of 5 for adverse channels having low or modest spectral coherence. This standard ATM875 modulation naturally supports 3 interleaved FDMA sets of 40 MFSK tonals and 2 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 1 Hadamard codeword were associated with 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 [27]. A drawback of FDMA signaling is the inefficient use of available bandwidth. Seaweb '98 testing was based on a very 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 objectives were 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 (radio acoustic comms) buoy pictured in Fig. 10. The "master" node was installed approximately 1500 m from the gateway node. These nodes formed cluster C, meaning both received and demodulated only the FDMA carriers of set C. The link between gateway and master nodes was extensively exercised during various multi-hour and multi-day periods to gather link statistics and to specifically improve the wake-up and synchronization schemes in the modem acquisition subsystem. Link reliability was monitored at the command center, with performance statistics tallied manually. This point-to-point testing identified specific suspected problems in the fledgling ATM875 implementation, and firmware modifications improved acquisition success from 80% to 97% of packets acquired.

Next, a 3-node subset of cluster A was installed as 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 meters in intervening waters! Various network interference situations were intentionally and unintentionally staged and tested until this simple but unprecedented relay geometry was well understood.

An unexpected benefit of the gateway node was discovered during these early tests. The gateway node was accessible from the radio-equipped workboat. Thus, functionality of a newly installed node could be immediately verified. Field personnel would use a deck unit and the gateway node for an end-to-end network circuit test including the new modem as an intermediate node, or they would bidirectionally ring the new modem via just the gateway route. Effectively, the work boat was a mobile node in the network equipped with both telesonar and gateway connections.

At this point, associate engineers from National Oceanic and Atmospheric Agency (NOAA) and Naval Surface Warfare Center (NSWC) visited Seaweb '98. They were brought by boat far into Buzzards Bay and a hydrophone was deployed over the side with a deck unit programmed to act as such a mobile network node. The visitors were permitted to type messages which were transported through the network and answered by personnel at the ashore command center.

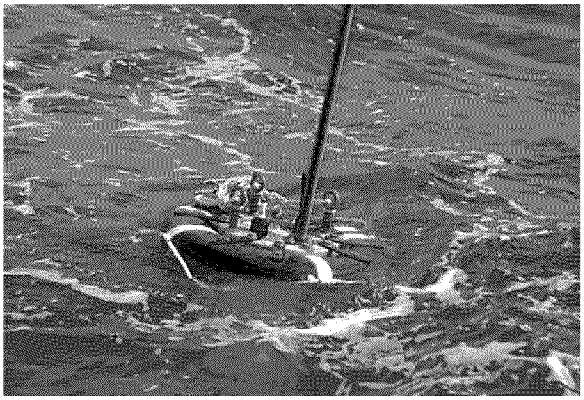


Fig. 10. In Seawebs '98, '99, and 2000, a Racom buoy provides a very reliable line-of-sight packet-radio link to Seaweb servers at the ashore command center and on the work boat. The radio link is a 900-MHz spread-spectrum technology commercially known as Freewave. In Seawebs '99 and 2000, additional 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.

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 inter-node 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 Fig. 11, and of doing specialized signal testing with the telesonar testbed [28]. In addition, the telesonar testbed was deployed in the center of the network for 5 data-acquisition missions and recorded 26 hours of network activity. The testbed also included a modem, permitting it to act as the tenth network node and giving ashore operators the ability to remotely control and monitor testbed operations. The testbed 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 the three weeks of September testing, 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. Data packets acquired by the oceanographic instruments were relayed through the network to the master node, on to the gateway node, and thence to the command center. The oceanographic instruments and modems generally operated according to pre-programmed 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 remote autonomous sensors. Data packets were delivered to 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. From the gateway node, reliable direct

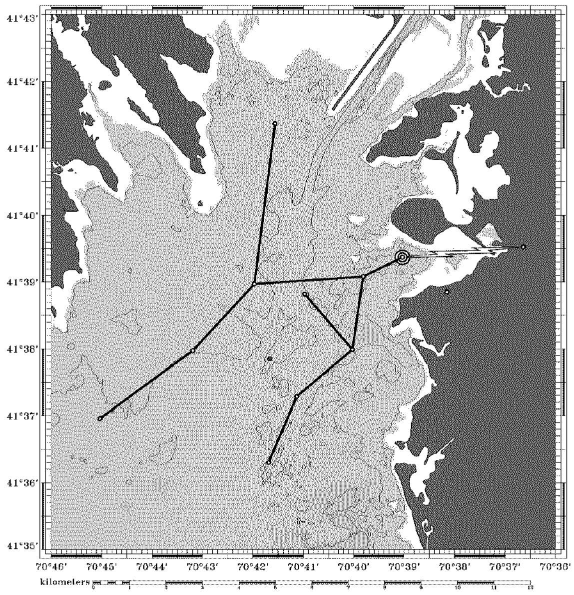


Fig. 11. Seaweb '98 demonstrated store and forward of data packets from remote commercial sensors including a CTD, a current vector meter, and a tilt/heading sensor (at the most northerly, westerly and southerly leaf nodes) via multiple network links to the Racom gateway buoy (large circle). Data packets are then transmitted to the ashore command center via line-of-sight packet radio. An FDMA network with three frequency sets reduced the probability 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.

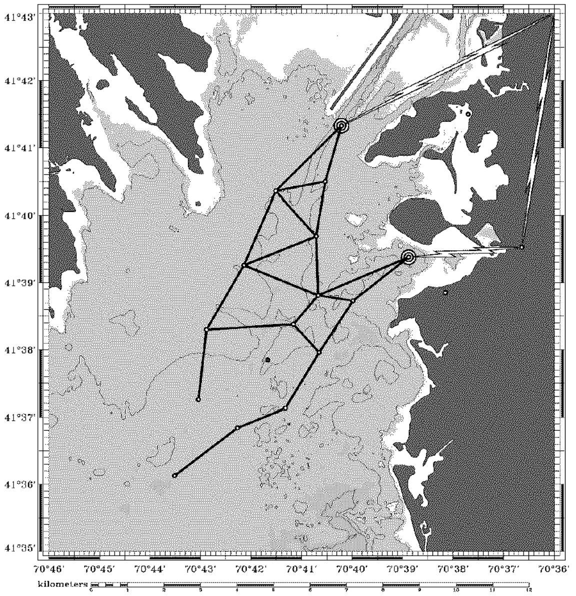


Fig. 12. Seaweb '99 explored the use of handshaking and power control. An ADCP sensor node, a tilt/heading sensor node, and a CTD sensor node generated data packets and the network routed them through various paths. The Racom gateway (easterly large circle) again provided a solid link to shore. A second gateway (northerly large circle) installed on a Coast Guard caisson near the Bourne canal provided a Bell Atlantic cellular modem link to the internet and thence to the command center. The Seaweb server running on a laptop PC managed both gateway connections and archived all network activity.

communications to a node nearly 7 km was achieved, suggesting the network could be expanded considerably more, in spite of the non-ducted 10-m deep channel. Seaweb '98 experience suggests that this environment could have supported 4-km links using the same ATM875 modems and omni-directional transducers. Attesting to the channel-tolerant nature of the MFSK modulation, a 3-km link was maintained during an early phase of testing 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 large ship transits through the field.

Seaweb '98 demonstrated the following network concepts: (a) store and forward of data packets; (b) transmit retries and automatic repeat request; (c) packet routing; and (d) cell-like FDMA node grouping to minimize MAI between cells. In addition, the following DADS concepts were demonstrated: (a) networked sensors; (b) wide-area coverage; (c) acoustic/radio interface (Racom gateway); (d) robustness to shallow-water environment; (e) robustness to shipping noise; (f) low-power node operation with sleep modes; (g) affordability; and (h) 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 (bits/s) and channel efficiency (bits-km/joule).

VI. SEAWEB '99

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 5-15 meter waters of Buzzards Bay. Network topologies involving compound multi-link routes were deployed and exercised. 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 repeat requests from the receiver.

The multi-access strategy was a new variation of FDMA wherein the six available 20-tone Hadamard words provided 6 separate FDMA sets, A through F. Rather than clustering the FDMA sets as in Seaweb '98, the notion here was to permit the server 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 was performed using 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 very 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 executes as a graphical set of LabView virtual instruments implemented under Windows NT on a laptop PC. An important function of 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.

Another test examined networking of automatic uplink sensor packets while simultaneously issuing server-generated downlink commands to deliberately poll sensors. In preparation for the "Front-Resolving Observation Network with Telemetry" (FRONT) application, large acoustic Doppler current profiler (ADCP) packets were synthesized and passed through the network with TDMA scheduling.

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. As a result, the final days of the test reverted to a prior stable version of the Seaweb '99 code and the 15-node network charted in Fig. 12 covered a less ambitious area than 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.

VII. SEAWEB 2000

Seaweb 2000 includes major hardware and firmware advances.

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 depicted in Fig. 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 (Nov. 1999), FRONT-1 (Dec. 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 round trip 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 begins exploring 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. It should be noted that all of these drawbacks are well known and FDMA was employed in Seawebs '98 and '99 primarily for ease of implementation as a simple extension to the rigid ATM875 telesonar machine code. The ATM885 permits a break from those restrictions.

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.

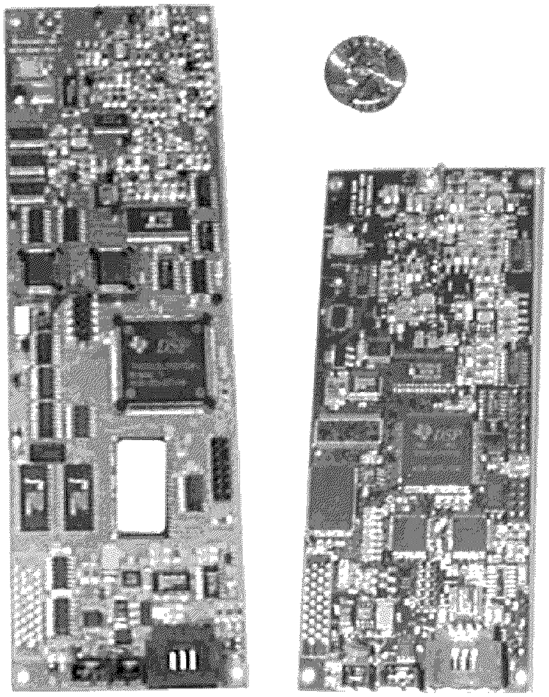


Fig. 13. The TMS320C5410-based ATM885 telesonar modem overcomes the hardware limitations of the TMS320C50-based ATM875s. The ATM875s served Seaweb '98 and '99. Seaweb 2000 will use ATM885s and networking development will benefit from faster processing, lower power draw, and increased memory. The ATM885 supports 100 MIPs and 320K words of memory compared with 25 MIPs and 74K available from the ATM875.

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 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.*, bit-error rate, automatic gain control, 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 time 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 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 [29]. This research uses the telesonar testbeds to record high-fidelity acoustic receptions and measure relative performance for numerous signaling methods. Seaweb 2000 will host SignalEx 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 will reach a level of stability and several experimental network tests will commence. These tests will explore the use of acoustic navigation methods for node localization, cost functions for optimized network routing, and statistics gathering for network traffic analysis.

Seaweb 2000 doubles as an engineering test for the FRONT-3 experiment to occur in 25-m to 50-m continental shelf waters. In keeping with the developmental approach, FRONT-3 will exercise stabilized Seaweb 2000 technology for an important oceanographic application.

In summary, the specific implementation objectives of Seaweb 2000 are: (a) packet forwarding through network, under control of remotely configurable routing table; (b) 64-bit header; (c) improved software interface between network layer and modem processing; (d) improved wake-up processing, *i.e.*, detection of 2-of-3 or 3-of-4 tones, rather than 3-of-3; (e) improved acquisition signal, *i.e.*, one long chirp, rather than three short chirps; (f) improved channel estimation diagnostics; (g) logging of channel estimates; (h) RTS/CTS handshaking; (i) configurable enabling of RTS/CTS handshake; (j) configuration of power control algorithm; (k) watchdog; (l) automatic-repeat-request (ARQ) feedback; (m) packet time-stamping; and (n) 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.

VIII. SUBLINKS '98 AND '99

An associated series of annual tests is exploring submarine participation as a mobile node in Seaweb networks. Sublinks '98 and '99 involved acoustic signaling between the research submarine *USS Dolphin* (AGSS 555), telesonar testbeds, gateway buoys, stationary autonomous bottom nodes, and the *R/V Acoustic Explorer*. The experiments are demonstrating digital, acoustic, underwater signaling to and from a submerged, moving submarine using developmental telesonar technology.

Sublink testing measures communication figures of merit as a function of controlled and measurable environmental parameters for candidate signaling modes. *Dolphin* executes free and controlled tracks around and away from the telesonar testbeds, varying her depth, speed, and telesonar transducer selection.

Aboard *Dolphin*, a COTS underwater telephone (EDO 5400) includes a fully integrated telesonar modem. This electronic system is interfaced to WQC-2 underwater telephone transducers on the sail (EDO SP23LT), keel (EDO SB31CT), and foredeck (EDO SB31CT). The Seaweb server control and monitoring station is located in a forward lab space adjacent to the sonar room with a serial interface to the underwater telephone. The lab space also accommodates a signal analysis station and a multi-channel digital audio tape recording system. This installation permits experimental wireless networked communications with autonomous, off-board nodes as illustrated in Fig. 14. Sublinks '98 and '99 used the ATM875 modem and Sublink 2000 used the new ATM885. All Sublink acoustic transmissions fall within the 8 to 10.5 kHz band for compatibility with the WQC-2 underwater telephone sonar system response. This "half-band" implementation was readily achieved by compressing the standard 5-kHz telesonar band and prolonging the MFSK signal chips by a factor of 2 to correspondingly tighten the spectral response.

Acoustic Explorer supports telesonar testbed operations and is the afloat command center. *Acoustic Explorer* remains moored south of the testbeds during *Dolphin* dives and monitors test transmissions with an over-the-side transducer and deck modem.

These experiments occurred on the Loma Shelf in the vicinity of 32°36′N, 117°21′W, 10 km west-southwest of Pt. Loma, San Diego, in waters 150- to 250-m deep. The site is conveniently accessed from the port of San Diego and is environmentally well characterized through historical surveys (*e.g.*, Seabeam bathymetry, geoacoustic inversions), prior ocean acoustics testing (*e.g.*, SwellEx), oceanographic measurements (*e.g.*, CTD), geometric measurements (*e.g.*, GPS), and acoustic channel probes. This operating area has a relatively flat bottom, sloping approximately 1° downward to the west, and is consistent with range-dependent assumptions for numerical propagation modeling. Most prescribed test tracks overlie a region with bottom slopes less than 0.5° extending roughly 10 km north and south, with a width of approximately 3 km. When range-dependent geometries are desired, the adjacent Loma Canyon and Coronado Bank offer complex bathymetry.

The submarine sonar is a Seaweb network gateway with the on-board Seaweb server providing an interface for the submarine command center. The server interprets

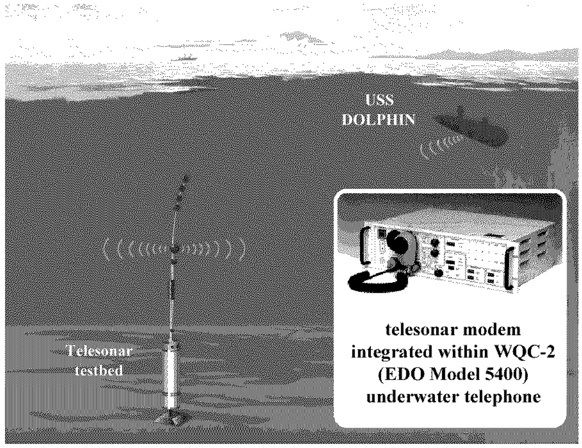


Fig. 14. Sublinks '98, '99, and 2000 demonstrated feasibility of telesonar links between submerged submarines and autonomous offboard devices. Autonomous devices included seafloor nodes such as the telesonar testbeds and surface buoys such as the Racom. Aboard the *USS Dolphin* research submarine, a telesonar modem was integrated with the pictured COTS underwater telephone electronics. These electronics provide connections to standard underwater telephone sonars operating in the 8- to 11-kHz band. The digital modem uses the analog sonar much as a computer modem uses the plain old telephone system. A Seaweb server running on a laptop computer aboard the submarine provides the user interface to the telesonar link.

messages and commands destined for the telesonar network, converts this information into bit strings compatible with telesonar modems, appends necessary headers and routing instructions, and directs the transmissions to a gateway node. The server interprets traffic from gateway nodes, time stamps the messages, logs the traffic, provides a graphical user interface, and maintains a database accessible to client stations.

IX. SUBLINK 2000

Sublink 2000 involved acoustic signaling between *Dolphin*, seafloor-deployed telesonar testbeds, a moored Racom-3 gateway buoy, telesonar listener nodes, and nodes suspended over the side of the moored *Acoustic Explorer* as shown in Fig. 15. Network gateways at the Racom and at *Acoustic Explorer* provided packet radio links to the internet via an ashore radio repeater. Links between all combinations of network nodes were tested while varying several different signaling and channel geometries. Highlights of Sublink 2000 include:

- An ATM885 telesonar modem was successfully integrated with an EDO 5400 underwater telephone and the *Dolphin* WQC-2 sonar. Three single-element WQC-2 transducers were individually tested. The ATM885 "half-band" mode was exercised using the 8-10.5 kHz band. This band is compatible with the WQC-2 sonars and with the telesonar/acomms interoperability standards established jointly by Navy research labs.
- Two autonomous telesonar testbeds were deployed to the seafloor and recovered 12 times using a new acoustically activated release method. High-fidelity transmission, reception, and data acquisition were verified.
- Six *Dolphin* dives were executed, each for approximately 6-8 hours. Telesonar communications from *Dolphin* to testbeds were achieved at maximum test ranges of 10 km. Channel-tolerant MFSK receptions were experienced at testbed nodes in spite of strong downward refraction and absence of ducts causing received signal energy to interact repeatedly with channel boundaries. Testbed-to-*Dolphin* links performed less reliably at the maximum ranges, largely because of lower source levels and higher receiver noise levels both contributing to a relatively lower SNR.
- Feasibility of *Dolphin* as the source of synthetic ASW contact reports was demonstrated, thus giving the green light for the planned Seaweb 2001 experiment in support of littoral ASW future naval capabilities.
- A complicated transmission cycle involving three transmitter platforms and multiple experiments was executed flawlessly in an interleaved TDMA schedule. Preprogrammed testbed missions were performed autonomously for the full duration of each experimental event.
- SignalEx transmissions were performed every three minutes using composite probe and eight different waveform suites, including contributed signals from Naval Undersea Warfare Center (NUWC), Polytechnic University, Northeastern University, Woods Hole Oceanographic Institution, Science Applications International Corporation (SAIC), Benthos, and Delphi Communication Systems (DCS) SignalEx transmissions used the 8-11 and 8-16 kHz bands.

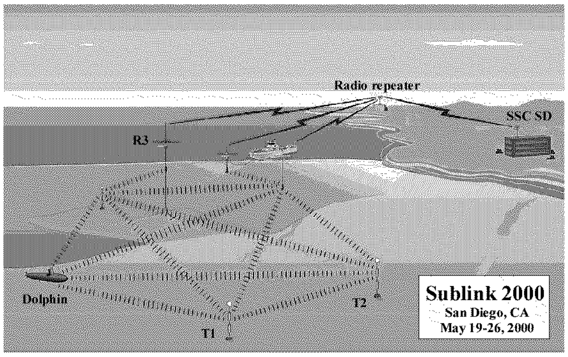


Fig. 15. Sublink 2000 was a TDMA network in 200-m waters with submarine connectivity to two telesonar testbeds (nodes T1 and T2) at ranges up to 10 km and with a Racom gateway buoy (node R3) at ranges up to 4 km. As a demonstration, standard email messages were generated by *USS Dolphin* at speed and depth and delivered to ashore users via internet.

- A new ATM885 "autobaud" implementation was exercised by means of a new ATT9 command causing the modem to sequentially transmit 14 64-bit Seaweb utility packets, each with a different modulation, coding, bit-rate or source level format. The receiving modem automatically and repeatedly processes all 14 modes.
- SignalEx and ATT9 data sets were collected between two testbeds on seafloor with separations of 3, 5 and 7 km. SignalEx and ATT9 data sets were collected between testbeds and submarine at 200-400 ft depths and 3-5 kt speeds over range-independent (200-m depth SWellEx benchmark channel) and range-dependent bottoms (over Loma Canyon and Coronado Bank).
- A Racom buoy with telesonar modem and Freewave radio provided gateway links to shore and ship. Shipboard personnel monitored all telesonar transmissions using an over-the-side telesonar modem and the Racom buoy 5 km distant.
- Seaweb servers aboard *Dolphin* and *Acoustic Explorer* controlled remote modems and archived incoming packets.
- Emails from transiting, submerged *Dolphin* were delivered via telesonar, Racom gateway buoy, and Seaweb server to the Office of Naval Research (ONR), Submarine Development Squadron Five, and to the family of a young sailor.
- GPS navigation data were recorded on *Acoustic Explorer* and inertial navigation data were recorded on *Dolphin*. All testbed deployment stations were well documented and well within specified placement tolerances.
- Excellent environmental (CTD) measurements revealed a prevalent thin layer of warm surface water overlaying a downward refracting sound-speed gradient.
- At-sea channel modeling and propagation prediction were performed using numerical physics-based telesonar

propagation models. Analysis of SignalEx channel probes confirmed predicted channel impulse responses and validated numerical channel models.

- The Racom-3 buoy, presumed lost after failure of a mooring line, was successfully recovered following a night-time search-and-rescue effort relying solely on experimental telesonar ranging technology.
- Several new Seaweb 2000 network functions were implemented on the ATM885 modem and exercised as incremental developments prior to the June FRONT-2 and August Seaweb 2000 experiments.
- ATM885 diagnostics were automatically logged, including SNR, AGC, and the number of corrected and uncorrected errors. Modems were intentionally driven to failure by systematic reduction in source level. The large cache of telesonar performance data with appropriate ground-truth measurements will support detailed comparative studies and parametric analyses.

X. FUTURE WORK

In 2001, stabilized Seaweb 2000 functionality will support the FRONT application (ForeFRONT-3 and FRONT-3 experiments) and the DADS application (Fleet Battle Experiment "India").

In late summer, Seaweb 2001 is scheduled to occur in a very large expanse of 30- to 300-m waters adjacent to San Diego, CA, and will incorporate several new fixed and mobile undersea systems as network nodes.

The annual Seaweb and Sublink experiments will continue to extend area coverage, resource optimization, network capacity, functionality, and quality of service. Active research feeding new technologies into Seaweb includes spread-spectrum signaling, directional transducers [30], in situ channel estimation, adaptive modulation, ad hoc network initialization, and node ranging and localization.

XI. CONCLUSION

Undersea, off-board, autonomous systems will enhance the war-fighting effectiveness of submarines, maritime patrol aircraft, amphibious forces, battle groups, and space satellites. Wide-area sensor grids, leave-behind multi-static sonar sources, mine-hunting robots, swimmer-delivery systems, and autonomous vehicles are just a few of the battery-powered, deployable 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.

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 the network architecture 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 gateways such as those demonstrated by Sublink and Racom are an essential aspect of the Seaweb concept. Command, control, and communications 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.

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