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COMMUNICATIONS PERFORMANCE OF AN UNDERSEA ACOUSTIC WIDE-AREA NETWORK

by

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March 2006

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COMMUNICATIONS PERFORMANCE OF AN UNDERSEA ACOUSTIC WIDE-AREA NETWORK

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Submitted in partial fulfillment of the
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ABSTRACT

The U.S. Navy is developing through-water acoustic communications capability for undersea, distributed systems. These wireless communication links form a wide-area network of fixed nodes consistent with future autonomous sensors on the seafloor. Mobile nodes may operate in the domain of the grid using the fixed nodes as both navigation reference points and communication access points. This thesis evaluates the experimental performance of such networked communications between an undersea vehicle and a ship. Physical-layer considerations include refraction, wind-induced ambient noise, and vehicle aspect angle.

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I. INTRODUCTION

This thesis examines the ability of an undersea vehicle to communicate through a distributed grid deployed on the ocean floor. Half-duplex acoustic links and long latencies due to the speed of sound through water are only some of the challenges encountered when implementing such mobile connectivity. In 2004, a U.S. Navy Seaweb experiment installed a Seaweb grid and achieved networked bidirectional communications with an underwater vehicle. This introductory chapter gives a brief description of the underwater wireless network and the fixed and mobile nodes used in the Seaweb 2004 Experiment.

A. SEAWEB UNDERWATER WIRELESS NETWORK

The Seaweb network is intended to provide command, control, communications and navigation for autonomous and manned nodes such as fixed sensors and instruments on the seabed, undersea vehicles, and surface vehicles operating in arbitrary ocean environments for various missions [1]. Seaweb is a distributed grid of interoperable telesonar (i.e., *tele*communications *so*und *na*vigation *r*anging) modems capable of supporting networked acoustic communications and node-to-node ranging. To be operationally practical, the communication system needs to be reliable, energy efficient, deployable, interoperable, flexible, affordable, and secure. The Seaweb grid is scaleable and its relatively short links permit physical-layer communications at high enough frequencies to support useful bandwidth, small transducers, directivity, deployable packaging, low battery power, and inherent transmission security (TRANSEC). Seaweb's architecture is consistent with the Navy mandate for distributed off-board sensors and vehicles.

B. NETWORKING WITH UNDERSEA VEHICLES

Mobile nodes have unique issues in maintaining connectivity within the Seaweb grid. Mobile connectivity is hindered by many factors associated with the telesonar physical layer such as the half-duplex links, the long latencies (speed of sound), and the range limitations of the underwater acoustic channel. While transmission loss from geometric spreading only depends on propagation range, absorption loss increases with both range and frequency, thus limiting the available useful spectral bandwidth. Channel behavior is similar to that of a waveguide but shadow zones can exist in the environment because of refraction and boundary effects. In addition to these detrimental propagation factors, the channel is further impaired by the possibility of high ocean noise levels from wind, shipping, and biologics.

Nevertheless, there has been substantial progress in the ability to operate manned and unmanned vehicles at depth while maintaining communications with the terrestrial world. While the provision for cellular addressing was incorporated into the Seaweb 2004 utility packets, the ability of a mobile Seaweb node (e.g. the underwater vehicle) to automatically maintain network-layer connectivity has not been fully implemented. This was overcome in this experiment with a special-purpose transport-layer protocol requiring the undersea vehicle to initiate all communications. As Seaweb advances technologically, the ability to maintain network-layer connectivity and communications will be further developed.

II. SEAWEB COMPONENTS

Seaweb 2004 was a collaborative experiment involving efforts from SSC San Diego, Johns Hopkins University, Naval Postgraduate School, and numerous other organizations. The Seaweb grid was installed along the outer continental shelf and was the largest deployed to date. The network was composed of 40 repeater nodes, three gateway buoys, two ships, and an undersea vehicle. The goal of Seaweb 2004 was bidirectional communications with an undersea vehicle operating within the context of the Seaweb grid. This chapter describes the components of Seaweb and their role in supporting the Seaweb 2004 goal.

A. SEAWEB MODEM

Figure 1. The ATM-885 telesonar modem is designed for use at depths up to 2000 meters. It is a self-contained, internally or externally powered modem with an integral transducer. It is capable of transmission rates from 150 bps to 15360 bps and can receive at rates from 150 bps to 2400 bps. It utilizes MFSK modulation. Channel-tolerance features include data redundancy, ½-rate convolutional coding, and multipath guard period selection [2].

All Seaweb 2004 modems were Benthos Inc. ATM-885 telesonar modems, built around the printed circuit board shown in Figure 1. The modems were upgraded with Seaweb Version 14.4 firmware owned and developed by the U.S. Navy. Version 14.4 retains all previously demonstrated Seaweb functions as discussed in Rice [1], with several upgrades. These upgrades include Doppler processing that permits node-to-node range rates in excess of 20 kts, the capacity to address up to 60 nodes, a refined Ping/Echo ranging function, and a new networked diagnostic command that remotely measures and reports link performance between arbitrarily specified node pairs.

B. SEAWEB GRID

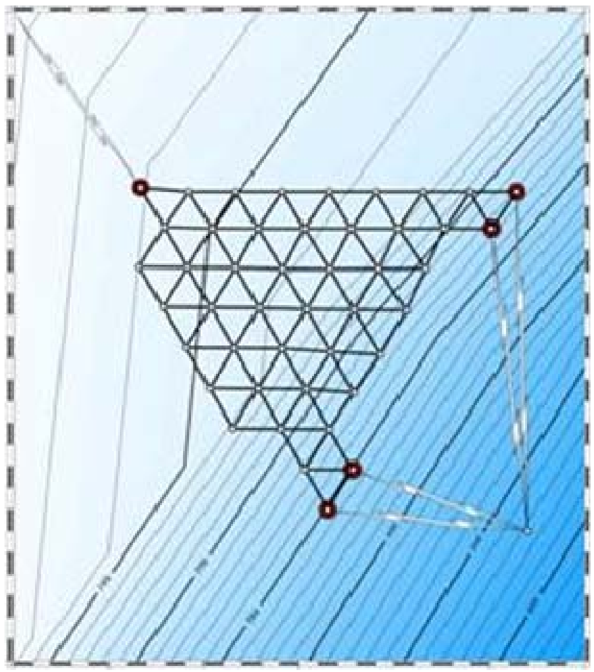
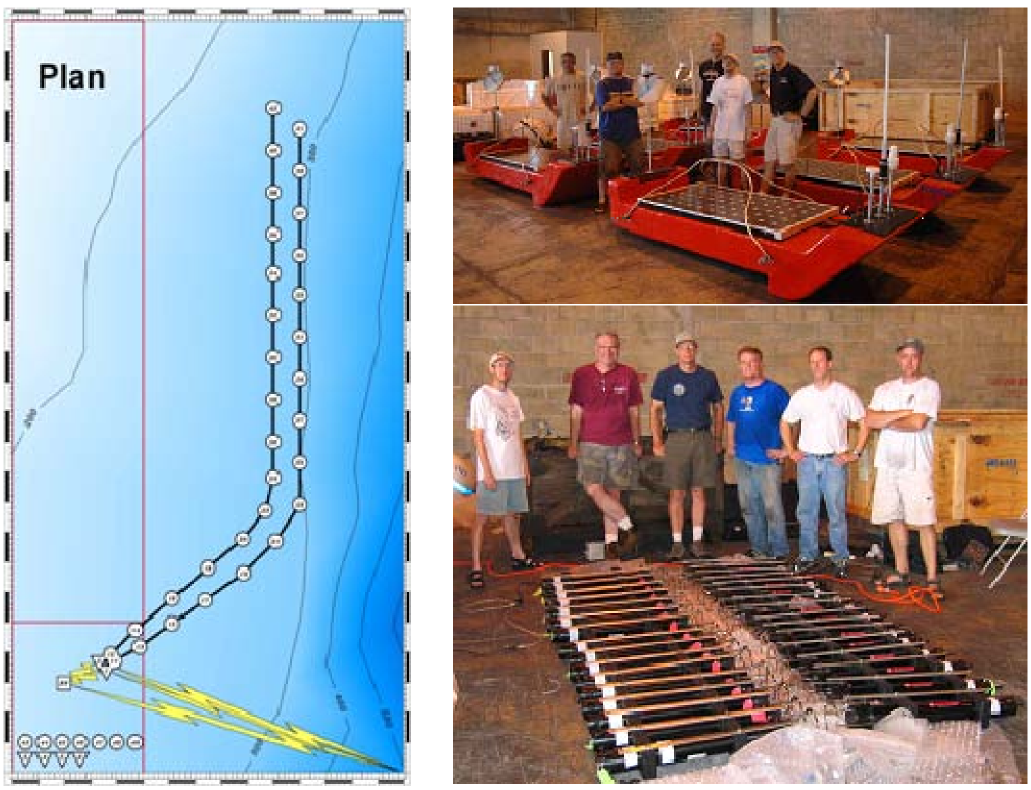


Figure 2. This originally proposed Seaweb network was a wide-area grid. The 4 racom buoys on the deepest contour would provide links to surface vessels in the deeper water, while the fifth racom provided a shore connection. Depending on mission requirements, Seaweb is able to flex and scale into any architecture provided enough nodes are available to support the acoustics of the through-water communications medium [2].

Seaweb topology possibilities are limitless due to the ad hoc fashion in which nodes can be deployed and networked together. Therefore, dependent upon the mission at hand, node deployment stations are chosen to provide the best communications coverage possible. The number of available nodes, weather conditions, and the ocean environment dictate the area of communications coverage provided by Seaweb. Historical propagation predictions, measured sound speed profiles, and ray trace diagrams are used to specify the nominal node ranges. The initially proposed Seaweb 2004 topology was a grid structure, as charted in Figure 2. As experiment planning progressed, the grid coverage was refined as depicted in Figure 3. Also shown in Figure 3 are components of the Seaweb 2004 network during experiment staging.

To mitigate experiment risk, a pilot grid was deployed and tested just prior to experiment commencement. The performance of that pilot grid and analysis of telesonar channel conditions guided the final design of the operational Seaweb network. Once the full grid was installed, three days were allocated for end-to-end testing that would have involved a second ship connecting with each node in the grid for connectivity tests between the two ships. Unfortunately, schedule compression due to adverse weather precluded the possibility of these 3 days of end-to-end testing.



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C. TELESONAR REPEATER NODES

In Seaweb 2004, all telesonar repeater nodes were hand-deployed from a large ship advancing at six knots. Figure 4 depicts the deployment, rigging and posture of the repeater node. By virtue of an acoustic release, the repeater nodes are recoverable for post-experiment reuse, for mid-experiment servicing, or for mid-experiment redeployment to more advantageous locations. The acoustic release connects the telesonar modem to the anchor fixing the node to the seafloor. Deployment latitudes and longitudes are logged to aid in node recovery and network analysis.

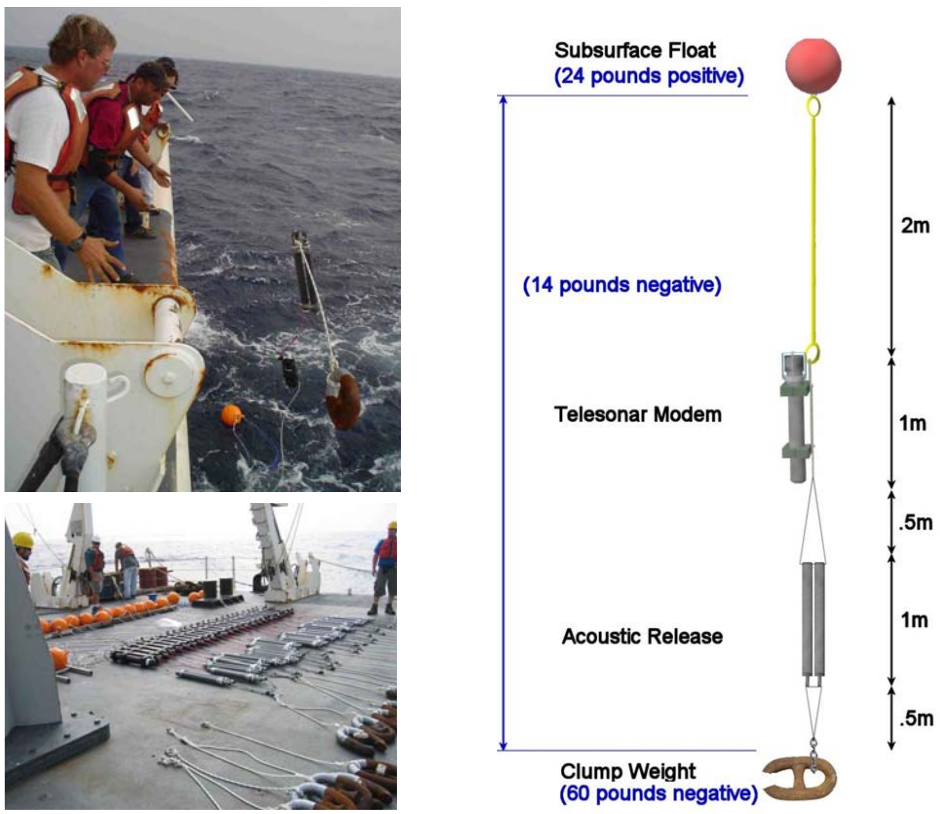

Figure 4. The telesonar repeater nodes were deployed from the deck of the second ship. It is possible to rig them to be deployed off of a small RHIB, rigid-hull inflatable boat. The deployed assembly rises just 5 meters above the seafloor and is then recovered by remotely commanding the acoustic release. The modem itself is suspended roughly 3 meters above the seafloor. The burn wire within the release corrodes and within five minutes, the attachment separates from the expendable weight and the node floats to the sea surface to be recovered by a RHIB. The telesonar modems operate at acoustic frequencies 9-14 kHz. The acoustic release transmissions occur at 33 kHz [2].

The stock telesonar modems operate in water depths to 2000 m. Alternative pressure housings permit operation to 10,000 m depths. The acoustic releases procured for Seaweb 2004 are rated only to 300 meters according to the manufacturer. However, during this experiment the repeater nodes were deployed in waters up to 350 meters deep without failures.

D. RACOM BUOYS

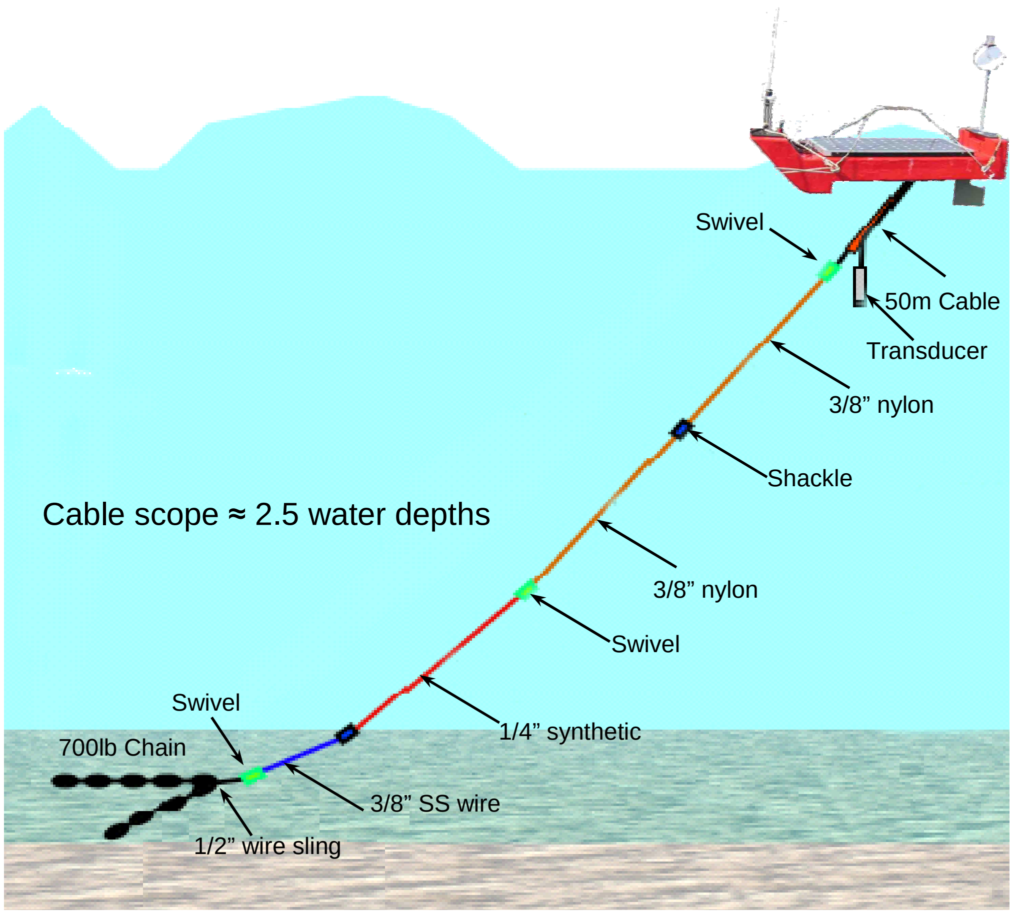

Figure 5. The Seaweb 2004 racom buoy is a low-drag small-cross-section buoy tailored for survivability in strong ocean currents. The solar panel provides energy during daylight in order to conserve battery energy. A microprocessor processes onboard sensor and GPS inputs and controls and buffers connections between the telesonar, Iridium, and FreeWave modems. The transducer is situated approximately 50 meters down the mooring cable to maximize use of the downward refracting channel characteristics [3].

Racom, radio acoustic communication, buoys provide the gateway link between the undersea network and the users. The racom buoys used in the Seaweb 2004 experiment incorporate FreeWave radio technology as well as Iridium satellite communication technology. The FreeWave radio provided a line-of-sight radio link between the racom buoy and the ship. The Iridium satellite communications link provides an alternative to the line-of-sight FreeWave link, but it was not used in Seaweb 2004.

The new low-drag design of the racom buoy is well suited for operating in strong ocean currents. A numerical drag analysis aided in optimizing the scope of the mooring line and in determining the anchor requirements. The buoys were anchored to the seafloor using a 2.5:1 scope-to-depth ratio on the mooring line. Using the above dimensions, the 220-meter water depth at the designated racom mooring station produced a 500-m radius watch circle around the anchor position [3]. The buoy and mooring design are illustrated in Figure 5.

The racom buoys were deployed from the stern of a ship while underway ahead slow into the current. The racom buoy was deployed buoy first, with slow payout of the mooring line culminating in release of the anchor at the desired mooring coordinates. Because of the severity of sea state and currents at the site, the racom buoys were expected to be a vulnerable link in the Seaweb 2004 network. Two racoms were deployed prior to beginning the experiment and an additional racom was deployed on the fourth day of the experiment for redundancy. Three additional spares were on deck of the second ship. [3]

E. SEAWEB SERVER

The ship and undersea vehicle each host a Seaweb server. The Seaweb server on the ship was designated the Seaweb administrator with power to establish Seaweb network-layer routes and specify Seaweb link-layer protocols. The network-layer routes are defined by neighbor and routing tables stored on the distributed modems. These tables may be remotely modified by the Seaweb administrator. The Seaweb administrator may remotely control the physical layer parameters such as bit rate, coding parameters, and source level by manipulating register settings in the modems. [4]

The server also provides the interface between the Seaweb network and client applications. The Seaweb server connects a client end-user to the underwater acoustic network through a TCP/IP socket connection. The server queues client outgoing data in a message database table and archives the data packet in the modem messages table. Then it transmits the packet to the acoustic network through the racom gateway buoy. Many types of links between the server and the racom gateway buoy have been previously demonstrated. These links include FreeWave line-of-sight packet radio, cellular digital packet data (CDPD), Iridium satellite modem, and U.S. Navy submarine sonars. The racom gateway node links the Seaweb server to the undersea network through standard TCP/IP and RS232 serial protocols. Acoustic network command and control determines the destination of the data packet based on the IP address, port number, and source/destination id numbers of the acoustic telesonar modems and the client's Seaweb subscription. [4]

The servers on the ship and undersea vehicle automatically logged the Seaweb 2004 network activity examined in subsequent chapters of this thesis. The database timestamps, archives, and queues all incoming and outgoing data, client information, and network statistics. During operations, the server publishes incoming data packets to the database for access by terrestrial clients, and queues outgoing data packets to the database for delivery into the underwater Seaweb domain. [4]

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III. EXPERIMENT ENVIRONMENT

This chapter discusses the environmental variables, including the historical data influencing the Seaweb 2004 plan and the measured data observed during conduct of the experiment.

Knowledge of the environment is vital to understanding communications performance and to the design of a successful network topology. The environment determines the characteristics of the telesonar channel and the communications link budget. The channel is determined by the source-to-receiver geometry, transmission loss, noise, multipath, and temporal variability. Seaweb 2004 employs signaling technology that is immune to expected multipath and temporal variability, as discussed in the next chapter.

A communication link budget derives from the source level of the transmitter, the noise level at the receiver and the range-dependent transmission loss [16]. Seaweb 2004 operations are affected by sound propagation and ambient noise levels for the operating band of 9-14 kHz.

A. CHALLENGES OF THE UNDERWATER ACOUSTIC CHANNEL

Signals travel much slower in underwater acoustic channels than in conventional communication channels. For example, the propagation speed is five orders of magnitude slower than that of the radio channel, producing communications latency and potentially resulting in a reduction of the overall throughput of the system [11].

In addition, the signals suffer significant losses proportional to the transmission range. Transmission loss can be attributed to two main factors, attenuation and geometric spreading. Attenuation is caused by absorption due to the conversion of acoustic energy into heat. It increases with distance and frequency. Geometric spreading refers to the diminishing of sound energy density as a result of wavefront expansion. It increases with distance at a rate dependent on the channel geometry. Two simple descriptions of geometric spreading are spherical, which is seen mainly in deep ocean water, and cylindrical, which is seen in shallow water and in ducted channels. [11]

The spreading characteristics of deep ocean channels have been explored extensively in the literature. Shallow water channels, however, exhibit greater variability and are less readily described. Signals experience dispersion from surface and bottom interactions and distortion from the combination of multipaths at the receiver [9]. Multipath propagation can cause inter-symbol interference (ISI) when the symbol period is less than the channel impulse response. Horizontal channels, like those in Seaweb, tend to experience rather long multipath spreads. This spread is predominantly a function of the water depth and the distance between the transmitter and receiver [11]. Doppler shift caused by movement of a communicating modem or by water currents can significantly degrade underwater communications. In general, the acoustic modem needs to monitor and correct Doppler shifts.

B. WIND AND SEAS

Sound propagation is influenced by sea surface conditions, the water medium, and bottom characteristics. Without knowledge of all these features it is difficult to predict the behavior of sound propagation [11]. The wind speed and wave heights during Seaweb 2004 were recorded on a daily basis shown in Figure 6. The weather conditions steadily improved through the experiment, decreasing the ambient noise level within the channel and improving the communications link budget. [5]

The noise level within a channel directly impacts the communications link budget. Most ambient noise can be characterized as having a continuous spectrum and Gaussian statistics. It is related to the movement of water including tides, currents, storms, and rain as well as seismic and biologic phenomena. Man-made noise is primarily caused by machinery noise (pumps, reduction gears, power plants) and shipping activity. Man-made noise dominates in areas of especially heavy vessel traffic [11]. In the 9-14 kHz band used for telesonar signaling, the ambient noise levels during Seaweb 2004 appeared to be associated with wind speed and sea state, consistent with historical noise spectra summarized by Figure 7 [12], with elevated levels episodically caused by shipping and sonar activity. In addition, multi-user communications by Seaweb itself increases in-band noise levels.

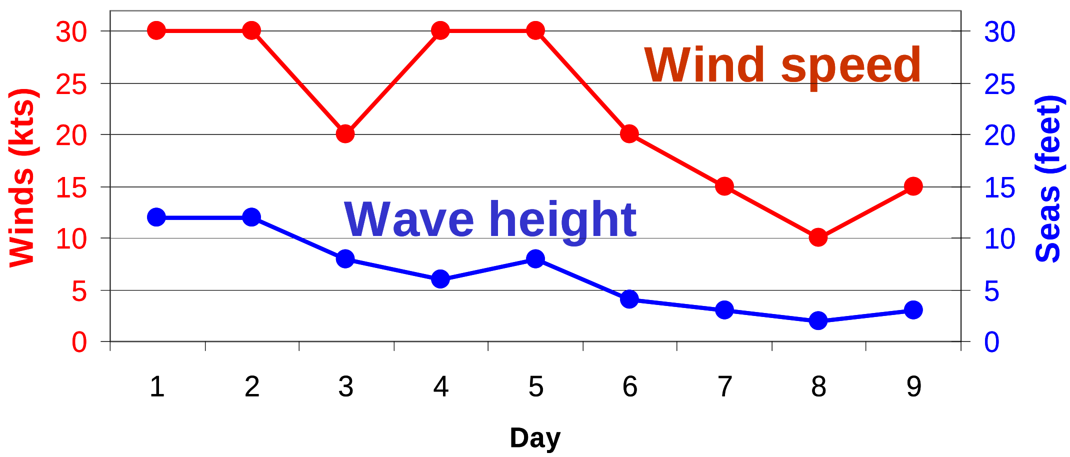

Figure 6. The wind speed and wave height were measured on a daily basis. These phenomena largely determined the ambient noise level within the communications channel. Improved Seaweb performance as the experiment progressed is partly attributed to decreasing noise levels [2].

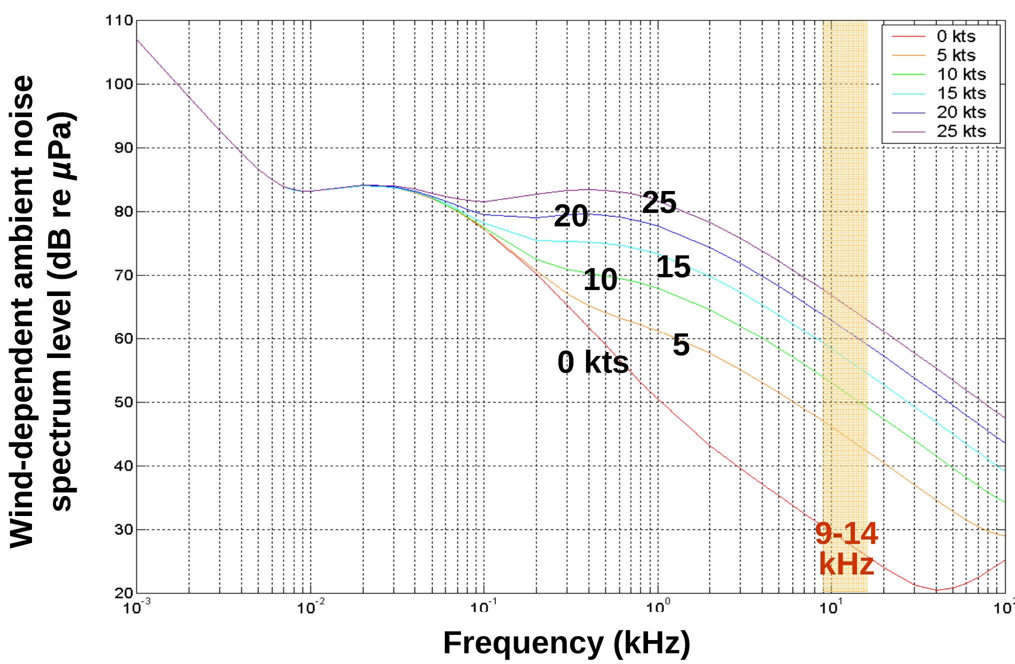

Figure 7. Weather conditions greatly impact Seaweb performance. The 9-14 kHz band is impaired by ambient noise from wind-dependent noise, as shown by historically derived noise spectra [12].

C. REFRACTION

Sound-speed profiles describing sound speed as a function of water depth provide information that helps predict telesonar communication ranges. Bathymetry or bottom topology at the site also plays an important role. The overall area of coverage served by the grid is determined by a combination of the number of nodes used, the distances between them, and the maximum communication range of the undersea vehicle.

When designing the planned Seaweb grid of Figure 3, the historical sound-speed profile shown in Figure 8 was used to model sound propagation for the experiment site and season.

The sound-speed gradient of Figure 8 refracts acoustic energy downward away from the sea surface. The rays traced in Figure 9 show sound propagation out to the first interaction with the seafloor with refraction modeled according to the gradients of the historical sound-speed profile. These ray-trace predictions were used to specify the nominal node spacing within the grid during experiment planning, assuming conservative link-margin estimates requiring direct-path acoustic communications. Such predictions afford the network designer an opportunity to deploy the Seaweb nodes in a sparser or denser pattern consistent with the tolerance of expected environmental propagation and noise conditions. For communications between nodes near the seafloor, downward refraction gives favorable propagation by virtue of the long direct-path arcs that are supported by the medium. Because performance can be severely degraded by interactions of the propagating acoustic signal with a rough sea surface, downward refracting channel conditions also favor communications from the undersea vehicle to bottom-mounted nodes. In this experiment, where reliable link-layer communications supports the objective of network-layer performance analysis, direct-path communications is the design criteria for node-to-node link-layer spacing. This is an admittedly conservative objective given prior link-layer performance measurements, but the network-layer performance is the overriding consideration in this experiment.

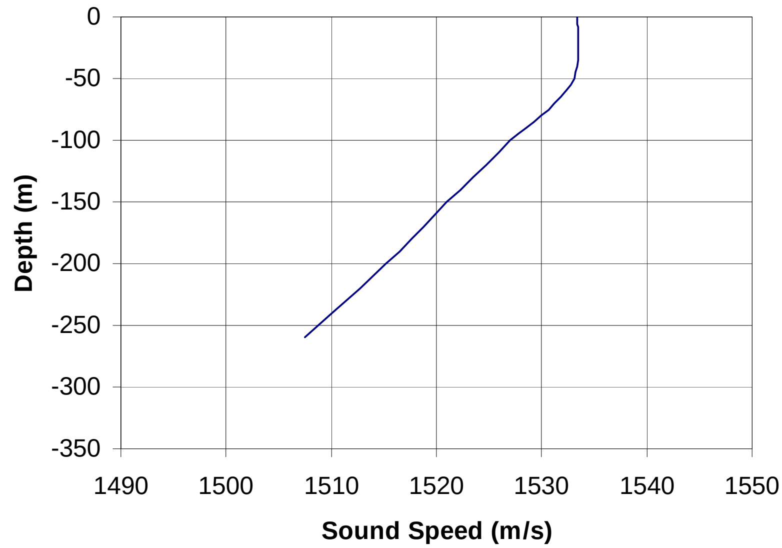

Figure 8. Historical sound-speed profile for the experiment site indicates a 50-meter deep surface mixed layer overlying a strong thermocline [6]. These are typical characteristics of continental shelf ocean waters in temperate zones.

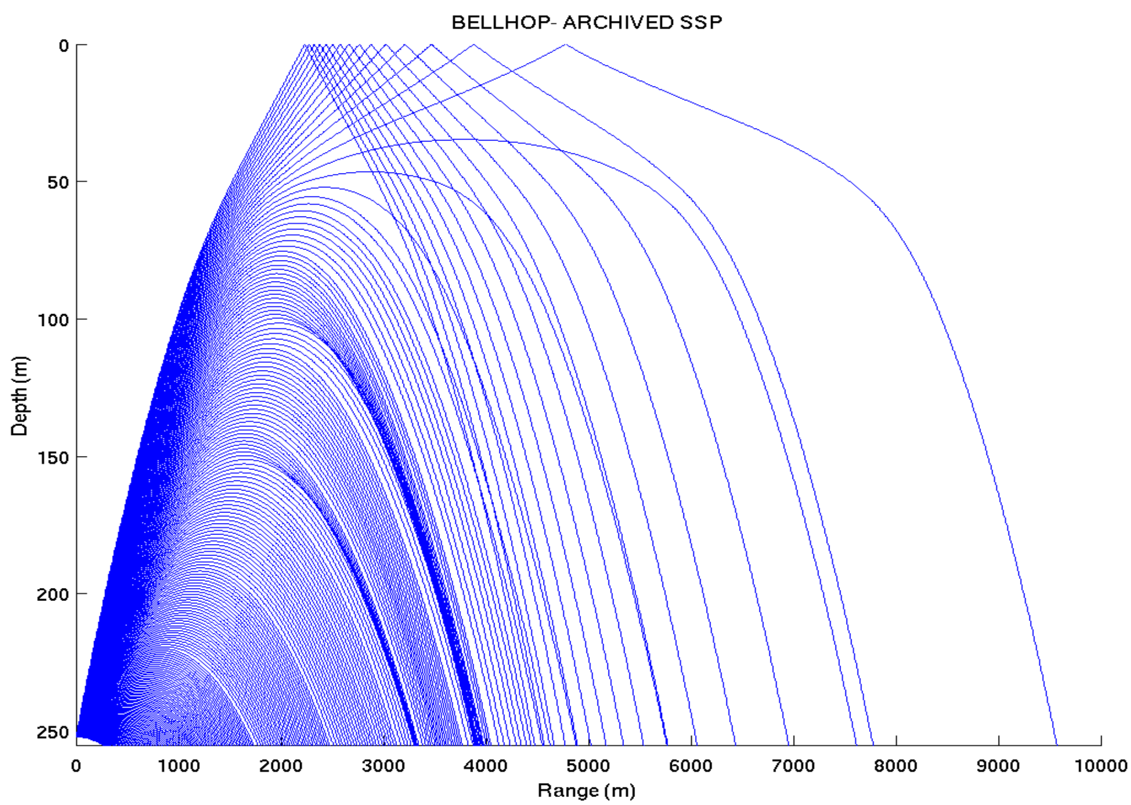

Figure 9. For an acoustic transmitter 3 meters above the seafloor at range 0, a fan of 223 rays with launch angles between 0° and –11.1° are numerically traced through a 255-m deep stratified medium modeled after the historical sound-speed profile of Figure 8. [6].

So, ray-trace analysis of the historical sound-speed profile suggests that direct-path sound energy would support node-to-node spacing up to 5 km. Direct-path propagation is a desirable condition since propagated energy is less subject to distortion and dispersion at the rough sea surface boundary, and to entrapment in surface ducts. Seaweb mission planners set the nominal distance at 3 km to ensure direct-path energy and to mitigate the less predictable noise levels. The 3-km spacing also allows for the possibility of individual node failures requiring longer links to heal the network. Moreover, a conservative design using 3-km spacing was consistent with the application of experimental Seaweb technology to undersea vehicle cellular communications, the principal objective of this experiment. It is expected that longer links involving non-direct path links are supportable, based on prior experimentation in other environments, but these links are not to be counted on given the experimental uncertainties of propagation and noise conditions.

Five days prior to the commencement of the experiment, during Seaweb deployment operations, the second ship obtained conductivity-temperature-depth (CTD) profiles in the vicinity of the network. Sound-speed profiles derived from these CTD profiles are plotted in Figure 10. The shape is generally consistent with the archival profile of Figure 8, exhibiting in the upper water column a well-defined mixed layer of slightly-increasing sound speed with depth, overlying a thermocline with sound speed decreasing strongly with depth.

However, because of turbulence from major storms, the mixed layer extends to about twice the depth shown on historical sound-speed profiles for the area at this time of year. Three sound-speed profiles representing geographically separate parts of the network are shown for clarity in Figure 11. Differences from the historical profile are in the depth of the surface mixed layer and thermocline. The mixed layer depth varies between 70 and 125 meters, compared with 50 meters in the historical profile. Some profiles show perturbations from a constant gradient in the thermocline and evidence of a bottom layer having a gradient distinct from that of the thermocline.

These measurements provided the acoustic propagation information intended to influence the final grid design, had the deployment of the operational grid not been accelerated by the compressed schedule. For the bottom-to-bottom acoustic propagation, as seen in Figure 12, the observed sound-speed profiles should support direct-path telesonar ranges to about 2400 meters, only half of that predicted from historical conditions typical for that time of year. The nominal distance of the nodes had already been set at 3000 meters as a conservative spacing choice, and the actual communications link budget appeared to be adequate for reliable communications despite the less favorable propagation environment. Nevertheless, these weather conditions demonstrate the inherent channel dependence of acoustic communications, and the variability that affects the propagation medium.

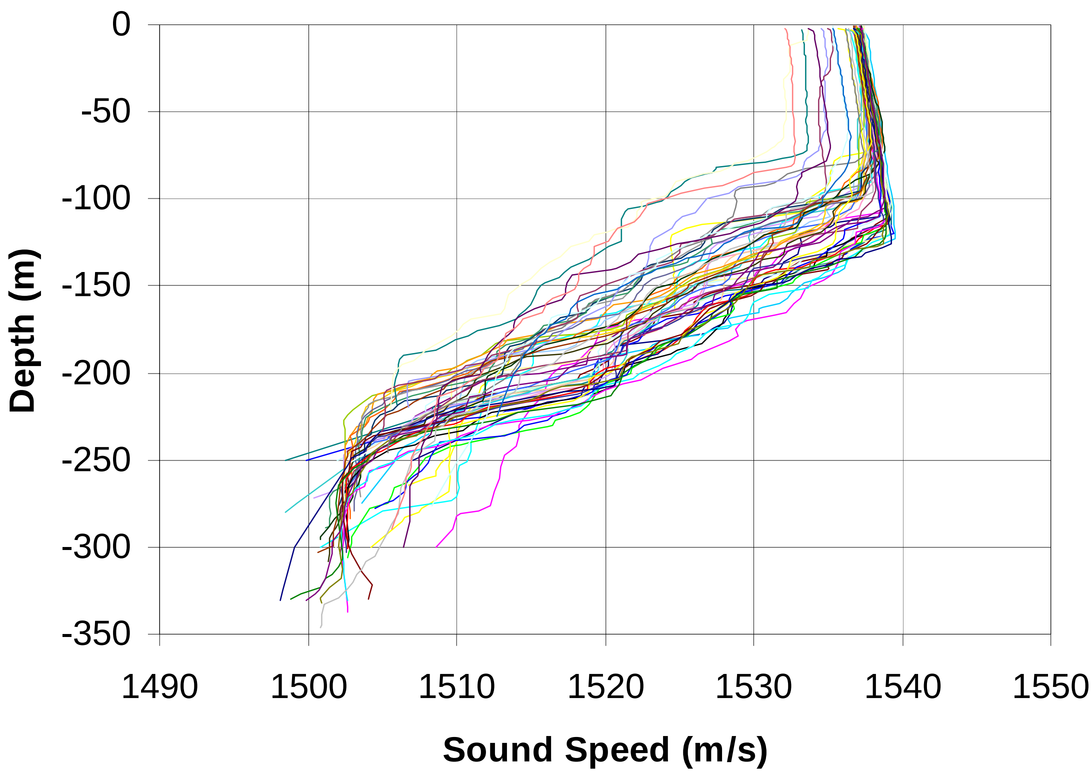

Figure 10. Sound-speed profiles measured during the experiment in the area serviced by the Seaweb 2004 network show considerable variability. [6]

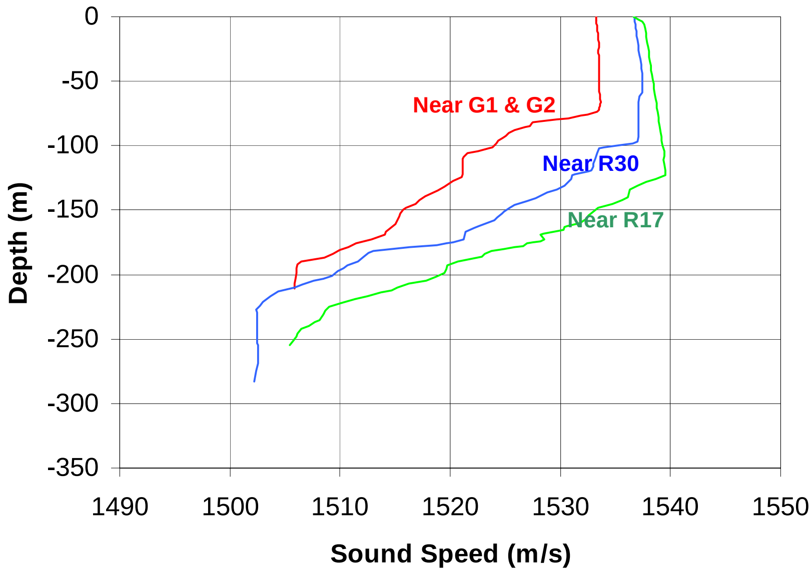

Figure 11. Selected sound-speed profiles showing variation of depth of mixed layer and thermocline and localized presence of bottom layer. Locations refer to Seaweb node addresses charted on Figure 3.

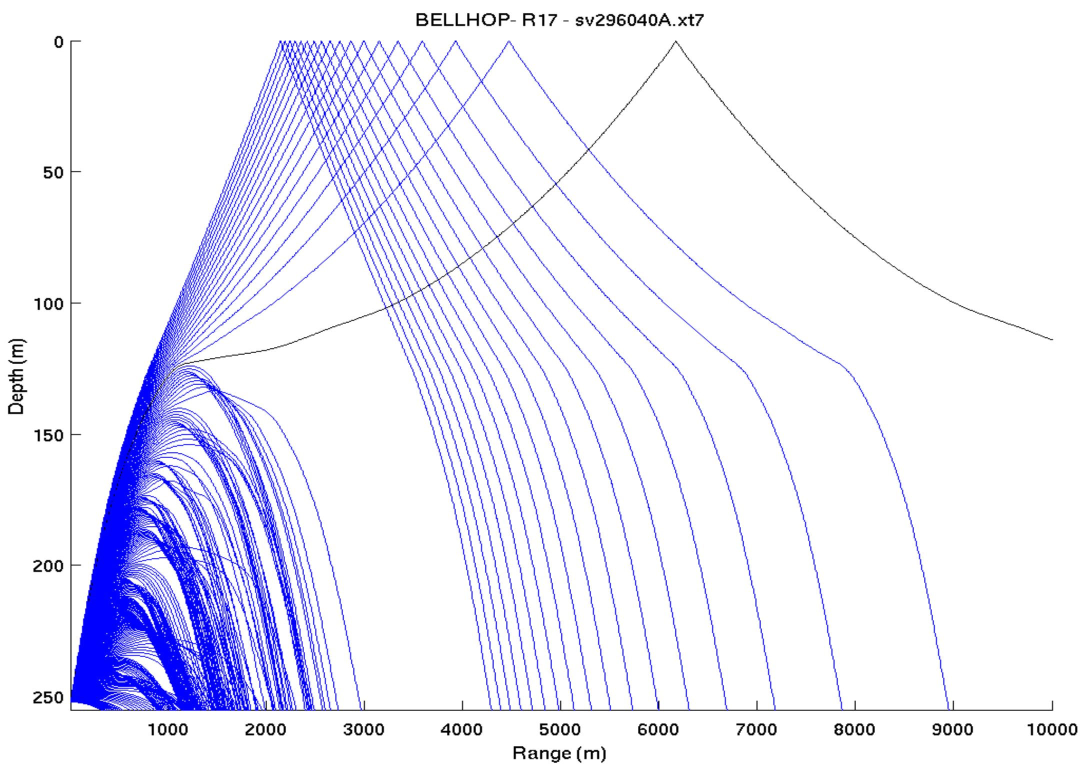

Figure 12. The sound-speed profile measured in the center of the grid near Node R17 is the basis for the above ray traces. There are 231 beams with launch angles between 0° and –13°. A 255-m depth is modeled for comparison with Figure 9. [6]

IV. SEAWEB 2004 COMMUNICATIONS

The communications architecture utilized in Seaweb 2004 follows the International Standards Organization's Open Systems Interconnection (ISO/OSI) model summarized in Figure 13. This reference model is designed to allow for efficient communications through seven subtask layers arranged in a hierarchical structure. Each layer of the model presents simplified information for further handling at the next higher layer. This chapter describes the Seaweb 2004 implemention of the physical and link layers. The next chapter examines the Seaweb 2004 network, transport, and session layers.

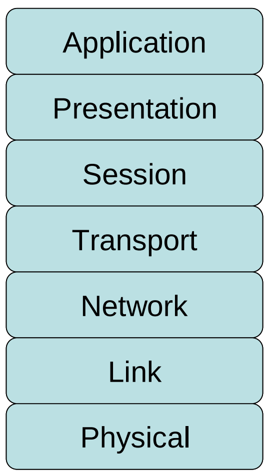

Figure 13. Seaweb underwater network is an implementation of the physical, link and network layers of the OSI model [7, 8]. The upper three layers are mission/application specific, and are normally implemented by the Seaweb clients.

A. PHYSICAL LAYER

The physical layer is concerned with transmitting an unstructured bit stream through the physical medium. It deals with the mechanical, electrical, functional, and procedural characteristics to access the physical medium.

1. M-ary Frequency Shift Keying (MFSK)

For Seaweb 2004, the physical layer is based on M-ary Frequency Shift Keying (MFSK) modulation of acoustic energy in the 9-14 kHz band. This modulation is favored for acoustic communications for its inherent tolerance of time spread induced by multipath and Doppler spread induced by temporal variability. Another advantage of MFSK is the ease of implementing receiver algorithms on a fixed-point digital signal processing (DSP) chip. The general analytic expression for MFSK modulation is $s_i(t) = \sqrt{\frac{2E}{T}}\left(\cos\left(\omega_i t + \phi\right)\right)$ for $0 \le t \le T$; i=1...M, where the frequency term ω_i has M discrete values, and the phase term, ϕ, is an arbitrary constant. The MFSK waveform changes frequency combinations from one symbol to the next. These transitions can be abrupt because there is no requirement that the phase be continuous. In practice, M is usually equal to a power of 2 and all M signals in the set are orthogonal signals, i.e. $\int_0^T s_i(t) s_j(t)\, dt = 0; i \neq j$. Frequency spacing requirements must be set to ensure orthogonality [14]. The Seaweb implementation of MFSK involves the use of 128 tones to attain a raw rate of 2400 bits/s.

2. Forward Error Correction Coding

Whether dealing with benign or impaired channels, received waveforms can have signal components lost due to low signal-to-noise ratios, fading, or interference. To mitigate these issues, the introduction of redundancy within a signal by means of coding, in effect, distributes the information contained in a single "bit" of data across sub-channels aiding in reconstruction of the signal [14]. This is called error correction coding. Seaweb utilizes forward error correction (FEC), redundant bits that are placed within a packet to aid in reconstruction and decoding if the signal is corrupted.

It is especially desirable within wireless links to employ a form of error correction that allows the receiver to correct errors in an incoming transmission on the basis of the bits in that transmission. By adding redundancy to the transmitted message, it is possible for the receiver to deduce what the original message was, even in the presence of bit errors.

The raw signaling rate of 2400 bits/s is reduced to an effective information bit-rate based on the desired degree of coding, redundancy and channel tolerance. Seaweb 2004 utilized convolutional error correction encoding at a ½ rate. Additional redundancy measures may be invoked to strengthen the signaling at the expense of net throughput. A nominal information bit-rate of 800 bits/s was planned with the ability to decrease to 300 bits/s if prevailing channel conditions warranted. In the actual experiment, the 800 bits/s information bit-rate was found to be reliable.

3. Transmission Optimization

The Seaweb design is gradually incorporating the ability to continually probe the channel, measuring the scattering function, the mathematical expression that describes the spreading of signal energy in the time and frequency domains. A handshaking process, discussed in section B, then optimizes transmission parameters in a process called adaptive modulation. The transmission parameters to be tuned through this process include source level, modulation, coding, and bit-rate. [15]

B. LINK LAYER

The link layer provides mechanisms for the reliable transfer of information through a physical link. Seaweb implements these mechanisms through the use of compact 9-byte utility packets. Even when in an energy-conserving sleep state, nodes are capable of receiving utility packets that perform functions such as link establishment, automatic repeat request, node-to-node ranging, and return receipts. Future link layer capabilities will support adaptive modulation [15] and network initialization functions. Figures 14 and 15 describe some link-layer mechanisms employed in Seaweb 2004 [2].

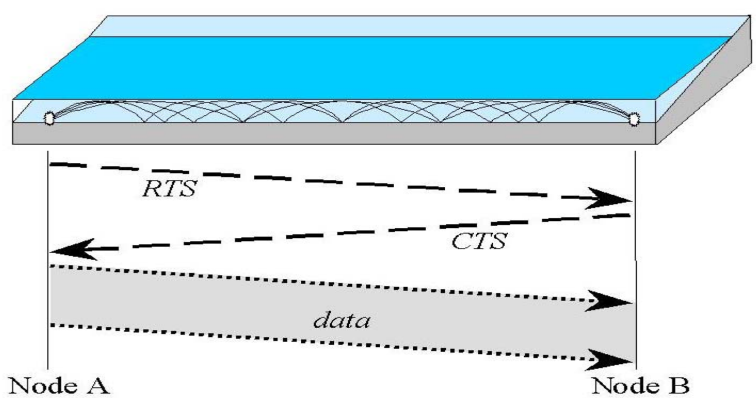

Figure 14. Seaweb link-layer handshake protocol for data transfer involves Node A initiating a request-to-send (RTS) utility packet. So addressed, Node B awakens and demodulates the RTS. Node B responds to A with a clear-to-send (CTS) utility packet [2, 8].

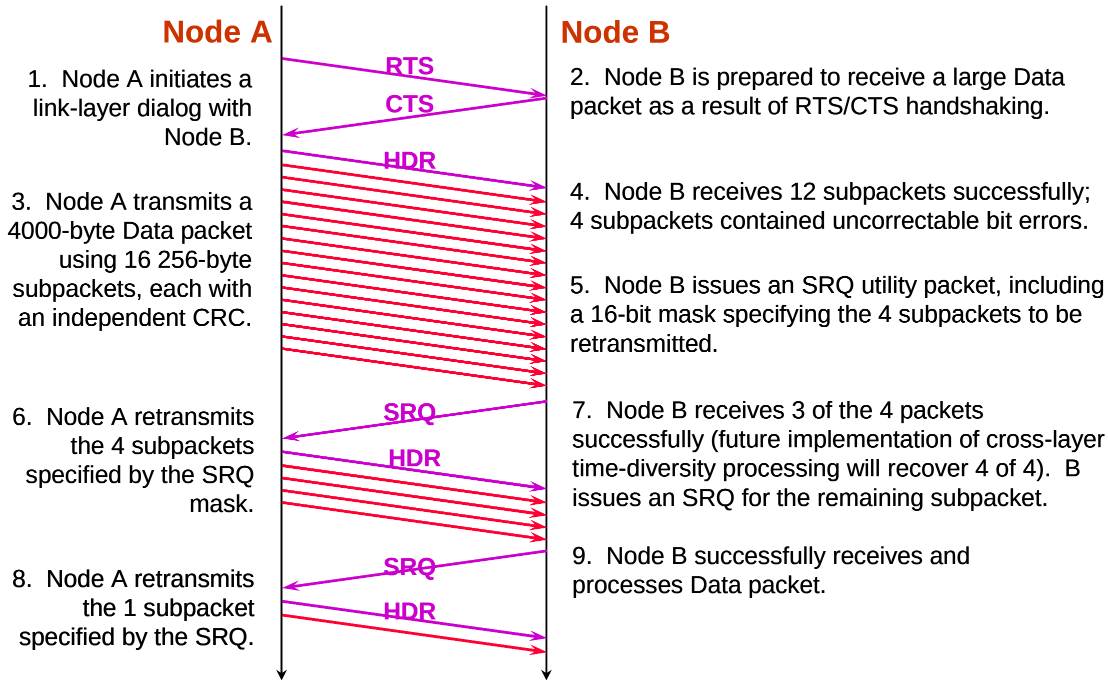

Figure 15. Selective automatic repeat request (SRQ) is a link-layer mechanism for reliable transport of large data files between neighboring nodes even when the physical layer suffers high bit-error rate. Purple arrows depict Seaweb utility packets including RTS, CTS, MAC header (HDR), and SRQ. Red arrows are Data subpackets [2, 8].

V. SEAWEB 2004 NETWORKING

The network layer controls the data routing and switching technologies used to connect systems. The transport layer involves source-to-destination addressing and information assurance mechanisms. Seaweb implements these network and transport capabilities on the modem. For Seaweb 2004, a session layer protocol was instituted to accommodate unique characteristics of a mobile node operating in a fixed grid. Performance metrics include availability, reliability, throughput, transit delay, transit jitter, and connection establishment delay.

A. NETWORK ROUTING

The network layer determines how messages are routed through the network from source node to destination node. As introduced in the previous chapter, Seaweb communications involves utility packets and data packets. The utility packets are 9 bytes, while Seaweb 2004 data packets may be up to 2 kilobytes. The utility packets of interest at the network layer are Receipts (RCPT) and Acknowledgments (ACK). Figure 15 shows the link layer movement of a data packet from node to node, representing just one hop in a network layer route that may have many such hops connecting source to destination node.

Seaweb 2004 did not employ an embedded, dynamic routing algorithm. Instead, the Seaweb administrator specified fixed routing by means of data structures maintained at each node. These distributed data structures are the Seaweb routing tables and neighbor tables. In Seaweb 2004 these tables were managed and manipulated only by the Seaweb administrator aboard the ship.

Routes are derived from a combination of the three routing approaches used in the development of internet routing protocols: distance-vector routing, link-state routing, and path-vector routing. Distance-vector routing requires that each node exchange information with its neighboring nodes. Each node then maintains a table of link costs for each directly attached node, and next-hop vectors for each destination node. A link-state router determines the link cost on each of its network interfaces, and advertises these settings to all of the nodes within the system. The individual nodes then monitor the link costs. With path-vector routing, information is provided about which nodes can be reached via a certain node. It does not account for the distance or cost estimate [14].

The Seaweb 2004 network required the administrator to estimate all of the above parameters and combine them in an ad hoc fashion to determine which routing scheme would best support message delivery. Seaweb routing will be automated as the technology evolves, and the Seaweb 2004 utility packet formats and network layer data structures anticipate that evolution.

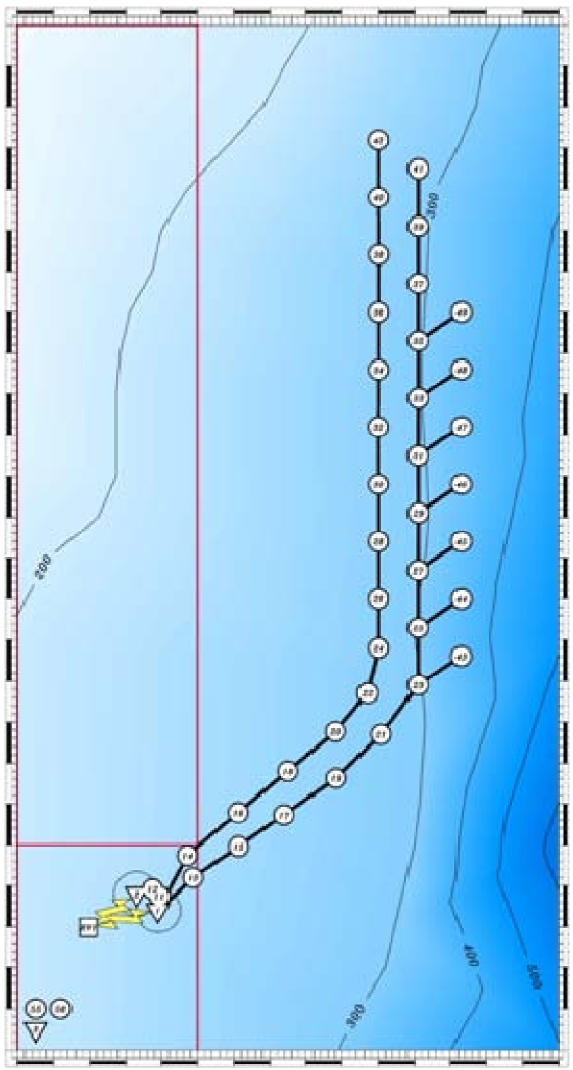

Figure 16. The initial deployed Seaweb operational grid included 2 racom gateway buoys and 39 telesonar repeater nodes. The gateway buoys are equipped with FreeWave line-of-sight radio links. The ship hosted the Seaweb command center, including the Seaweb server with FreeWave interface [2].

During Seaweb 2004, the ship was responsible for monitoring the performance of each node and the characteristics of each link, determining when and if the routing tables needed to be changed. When each node was deployed it had an initial routing table programmed within the modem. The original routing configuration is shown in Figure 16.

Channel/link characteristics changed throughout the experiment as a result of varying noise levels. As seen in Figure 6, during the first five days of the experiment, high winds and seas elevated the noise level, and decreased the link budget. Channel/link characteristics were also affected by trawling impact, examined in subsequent chapters. Nevertheless, a reliable 800 bits/s physical layer was available throughout the experiment.

Upon successfully reaching the destination node, if the return receipt flag is set in the data packet header, the transport layer automatically generates a return receipt and routes it back to the source node following an efficient and reliable RCPT/ACK link-layer mechanism.

B. MOBILE NODE INTEGRATION

Extreme channel variability between moving nodes is a major limitation for mobile underwater communication systems. In addition to the motion-induced pulse compression and dilation of received signals, the channel geometry and multipath structure change rapidly, limiting applicability of receivers requiring significant channel coherence. The Seaweb 2004 physical layer was relatively immune to these effects, by virtue of non-coherently processed MFSK modulation and special measures for Doppler tolerance.

A more serious challenge is the fact that the undersea vehicle in Seaweb 2004 was not an omni-directional receiver, unlike the nodes of the fixed grid. The undersea vehicle suffers as a receiver when its own hull obstructs arriving sound energy. These outages are dependent on its own orientation in relationship to the direction of incoming signal propagation. Additionally, the undersea vehicle is a relatively noisy receiver because of flow noise, propeller noise, and other mechanical noise. These combined factors make the mobile node a disadvantaged receiver compared to the fixed node.

C. SESSION PROTOCOL

The state of the art of Seaweb 2004 mobile connectivity compelled the use of a session-layer protocol requiring the undersea vehicle to initiate network-layer dialogs. The mobile node would declare the nearest node to be the cellular address, and would access the Seaweb route to the destination node via the cellular node. When the ship received the initiating message (data packet), it would reply with a response message (data packet) via the reciprocal route to the cellular node indicated within the initiating message, and the cellular node would directly address the mobile node. Upon receiving the response, the Seaweb modem on the undersea vehicle would immediately and automatically return a receipt to the ship, again via the cellular address and the fixed route. The Seaweb 2004 session-layer protocol is summarized graphically in Figure 17.

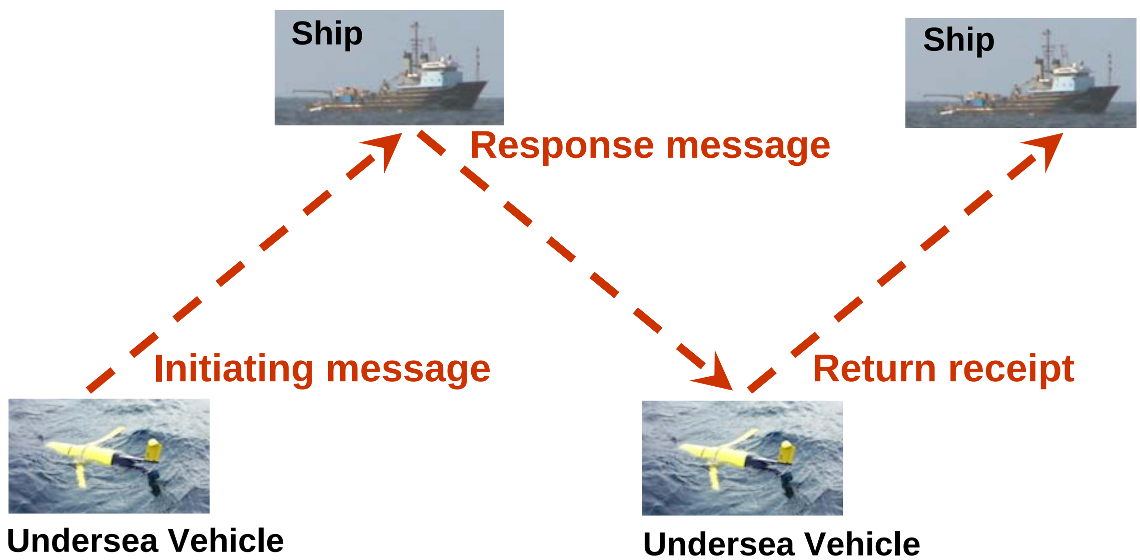

Figure 17. The communications protocol was such that the undersea vehicle would initiate all communications. The message flows through the grid, ultimately reaching the destination node, i.e., the gateway buoy. The ship would reply with a response message delivered through the grid. Then the undersea vehicle would send a return receipt to the ship through the grid. The Seaweb network layer routes the data packet through the grid based on the destination address and the routing tables [2].

VI. SEAWEB 2004 NETWORK GRID

A. DEPLOYMENT

The first step in implementing the Seaweb 2004 cellular grid was to perform in-air networking tests at an ashore facility. These tests occurred many days prior to the pilot grid deployment, and exercised message routing through the actual experiment hardware. The procedure involves physically arranging nodes adjacent to their neighbor nodes in the grid. Test messages are then sent from source to destination via the intended communications route through the network. This process enables operators to diagnose and fix potential networking and mechanical problems prior to deploying the Seaweb nodes in the water. After in-air testing was completed, all acoustic releases were assembled and rigged for deployment. Forty-seven telesonar repeater nodes and six racom gateway buoys were then loaded aboard the second ship and secured for the underway transit to the experiment site on the outer continental shelf.

Six days prior to the commencement of the experiment, a Seaweb pilot network consisting of 7 repeater nodes and 1 racom gateway buoy was deployed as charted in Figure 18. Basic ringing out of the grid indicated adequacy of the node-to-node spacing and grid design.

Then, during the afternoon and evening of the same day, the second ship deployed an additional 32 repeater nodes and 1 racom buoy, forming the operational grid of 39 repeater nodes and 2 racom gateway nodes charted in Figure 19. Based on time reports collected from the second ship, the average deployment time required per node was just 20 minutes, including node-to-node transit time [2].

Full deployment of the operational grid represented an accelerated evolution driven by several constraints, including a compressed schedule, incoming inclement weather, and avoidance of interference with other experiment platforms operating in the same area. A further impact of the accelerated schedule was the omission of a planned 3 days of end-to-end network testing between each node and the racom gateway. The operational network did not benefit from this pre-experiment checkout process and any fine-tuning that might have ensued.

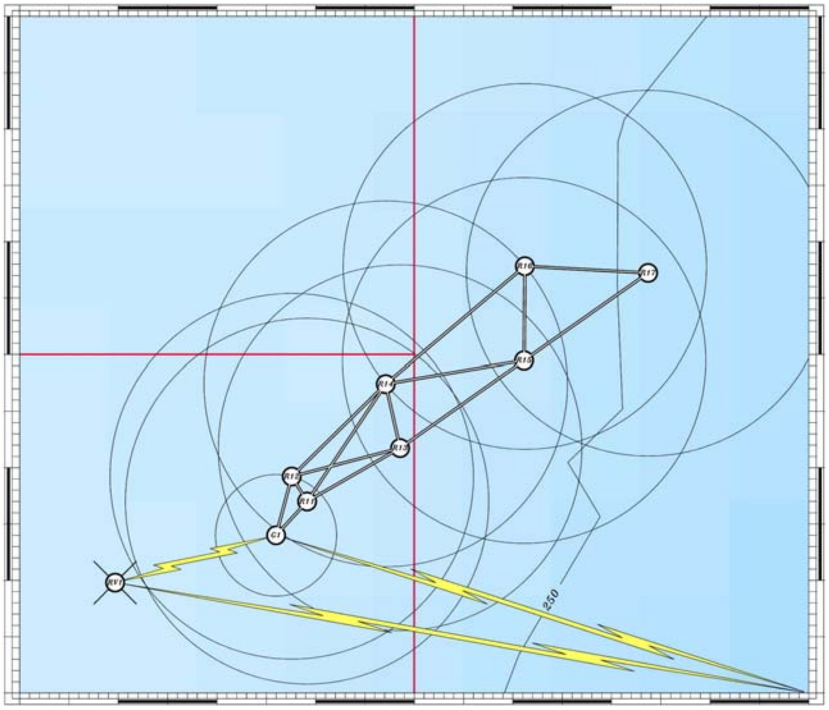

Figure 18. The Seaweb pilot network was a subset of the proposed operational network. It consisted of 7 repeater nodes at positions R11, R12, R13, R14, R15, R16, and R17 and 1 racom gateway buoy at position G1. The circles plotted here show conservative communications range estimates for each node—note the shorter range allowed for G1 where the telesonar transducer is less than 50 meters below the sea surface and therefore subject to shorter direct-path ranges to seafloor stations. The testing of the pilot grid by the ship moored at station "RV1" and measurements of the prevailing environmental conditions by the second ship reduced risks for the final network architecture shown in Figure 19 [2].

As part of the deployment process, the second ship moored 2 racom gateway buoys in the Southwestern portion of the network. The racom buoys require a more intensive preparation process, but took only 6-8 minutes to deploy. The moored racom buoys handled the high seas, high winds, and strong currents at the experiment site during this maiden deployment, however brief.

After deploying the bed of repeater nodes, it was decided that the second ship would recover the two racom gateway buoys. Warnings of inclement weather gave concern that the buoys would have been unnecessarily at risk. Sea states were too high for use of a RHIB to assist in the buoy recovery, so the ship went it alone. Both buoys were retrieved, but major damage incurred by the heavy-handed recovery process rendered them useless for the rest of the experiment. Both moorings were lost, both telesonar transducers were lost, both telesonar transducer cables were damaged beyond repair, one Iridium antenna was lost, one GPS antenna was damaged, and one FreeWave antenna was lost. Visual inspection indicated that the seas had not damaged the buoy portion, however [3]. This indicated that the new racom buoys are survivable in six to nine foot seas.

The most serious loss during the racom recovery was the two telesonar transducer cables. Although the second ship had four additional new buoys on deck, they only had one 50-meter telesonar transducer cable. This was a result of the short contract schedule in combination with the relatively long lead-time on the cables. Therefore, a 20-meter cable was fabricated by joining two available 10-meter cables. If this had not worked, the contingency plan had been to use a telesonar transducer deployed over the side of the ship in place of the racom gateway buoy [18].

One day prior to commencing experimentation, the second ship deployed two racom gateway buoys designated G1b and G2b in the vicinity of the two that were recovered previously. To avoid entanglement with remnants of G1a and G2a, the new buoy moorings were displaced slightly from the earlier posits. G1b stood approximately 500 meters east of G1a and G2b approximately 500 meters north of G2a [3, 18].

A problem at racom buoy G2b with the telesonar transducer or telesonar transduer cable prevented telesonar communications and was identified the same day of deployment. It was felt that Racom gateway buoy G2b needed to be recovered and serviced. The failure was isolated and confirmed by various means, including testing via direct telesonar communications from RV1 using an over-the-side telesonar deck unit. It was determined that when daylight and seas permitted, the second ship would execute a controlled recovery. All Seaweb repeater nodes were functional with exception of Nodes 20 and 35. They responded to Seaweb utility packets, but had difficulty with higher bit-rate data packets. This was thought to be due to the transducers being occluded by a fouled or tangled rigging. For this reason, the Seaweb routing avoided Node 20 for the first day of testing.

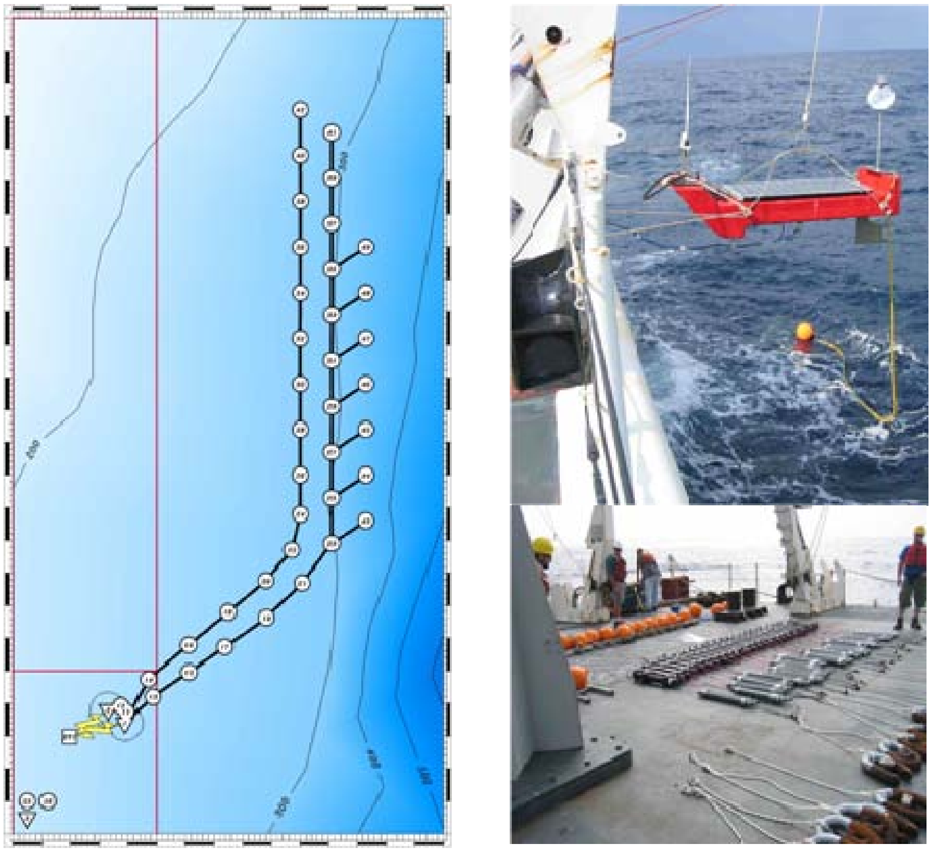

Figure 19. The actual grid of repeater nodes was deployed eight days prior to the beginning of the exercise. Due to inclement weather, end-to-end testing of the grid did not take place. Since the three days of planned testing did not happen, many troubleshooting types of errors were fixed during the ten days of testing. This is one of the reasons for steady performance improvements during the course of the experiment [2].

B. NETWORK REROUTING

During the post-experiment recovery of the repeaters it was confirmed that the central column of the Seaweb grid suffered major trauma by trawling activity. The inability to recover 8 of the repeater nodes is largely attributable to the trawling activity, with a variety of failure modes described in greater detail in Section C. Despite this damage, the Seaweb administrators on the ship incrementally established connectivity within the grid. Through remote polling and remote control of the Seaweb network layer, administrators healed the network. This significant achievement of the exercise anticipates future automatic initialization of ad hoc Seaweb grids, including the assimilation of nodes deployed by various platform types over time, including Unmanned

Aerial Vehicle (UAV), Unmanned Surface Vehicle (USV), Unmanned Undersea Vehicle (UUV), SEAL Delivery Vehicle (SDV), Maritime Patrol Aircraft (MPA), attack submarines (SSN), etc.

Day-to-day changes in the network routing are shown in Figure 20.

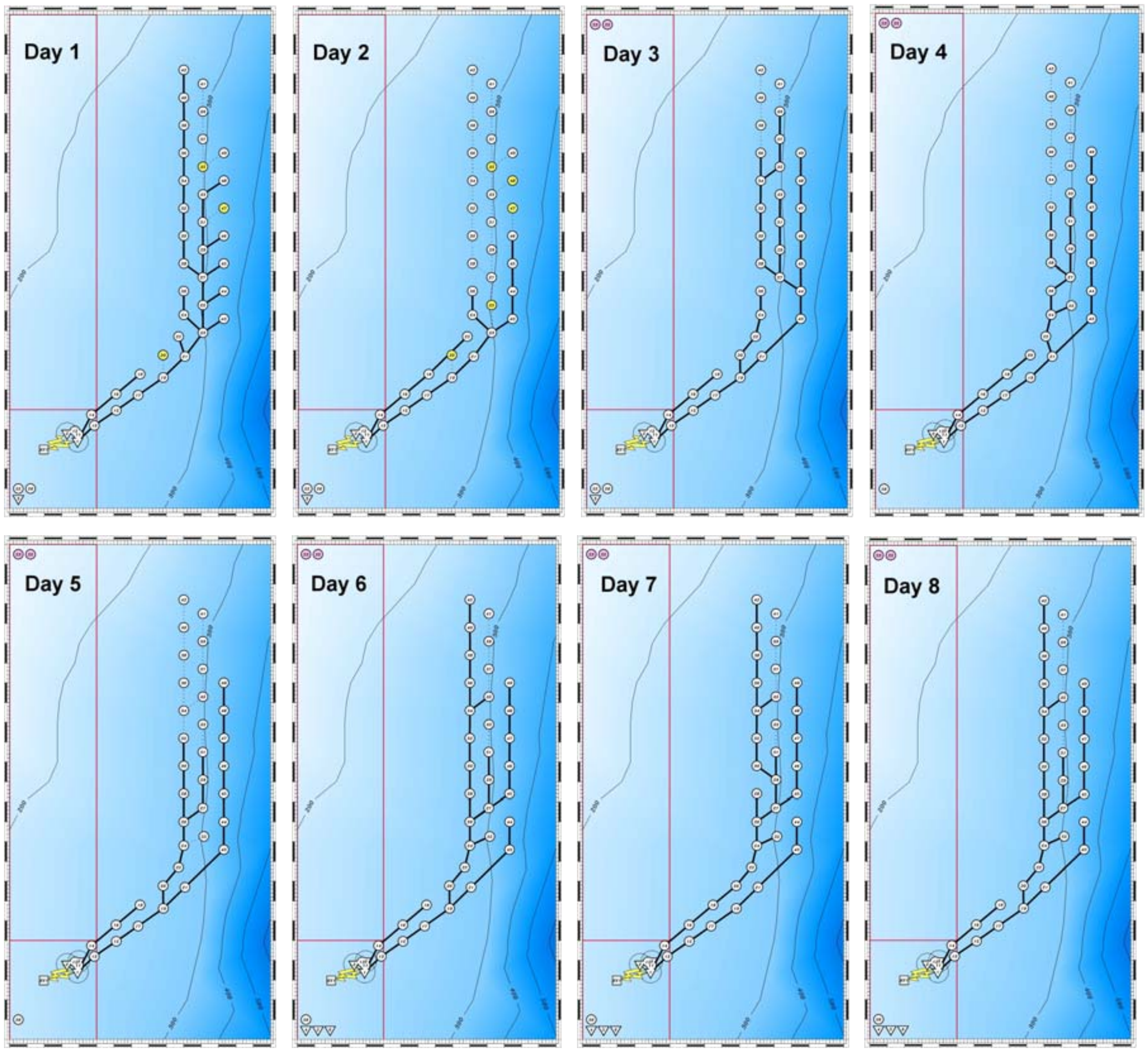

Figure 20. Day-by-day changes within the network were accomplished by remote polling and control from the ship. These charts demonstrate the impact routing can have on the overall performance of the network. They also support suggestions that the network can be healed post-major trauma. Initial routing relied greatly on the center 300-meter contour column of nodes. In hindsight, it is clear that had routing been accomplished sooner in the manner accomplished on Day 9 (Figure 21) with the center nodes as leaf nodes, Seaweb 2004 performance would have been improved.

1. Day One

During the first day of operations connectivity with the racom buoy via the FreeWave line-of-sight radio link was occasionally lost for long periods of time as the ship ventured away from the buoys. A FreeWave range of 4 nmi or less was needed for the ship to maintain uninterrupted connectivity since the low-profile racom buoy was periodically within a trough with the radio link momentarily occluded by a wave crest. In subsequent days, the ship was moored in position just 2 nmi from the racom moorings. At this range the ship maintained solid uninterrupted connectivity with the racom buoy. Testing of the grid continued throughout day 1. This included adjusting bit-rates from 300 to 800 bits/s, adjusting routes, and setting power levels. It is important to again note that the original schedule allowed for up to 3 days to ring out the grid, in conjunction with node servicing support from the second ship. Due to the inclement weather and all ships being sent back to port, this end-to-end testing did not happen.

The second ship had four spare telesonar repeater nodes, four pairs of acoustic releases, forty-one weights, and one spare float onboard. Four additional racom buoys, one ready for deployment, were on deck. Transducer cables proved to be the limiting factor for racom buoy availability. Two of the 50-meter cables were severed during the aforementioned recovery and the third was on the inoperative deployed racom. The working deployed racom had a makeshift 50-m cable created during the unexpected anchorage by splicing a 50-meter deck unit cable onto the stub of one of the severed cables.

There was not a significant amount of rerouting of the network on day one, since the network needed to remain available for use by the undersea vehicle. With limited Seaweb personnel on the ship, the Seaweb server could not be manned around the clock. Seaweb personnel rested during the afternoon and evening hours in order to prepare for the day 1 events. Occasionally the communication link between the ship and the racom buoy would drop out due to high seas and maneuvering of the ship. These outages required reestablishment of the communications session and interrupted Seaweb service. Outages usually were on the order of minutes, but in one case was over 30 minutes. Without access to the gateway, it was difficult to maintain and monitor all aspects of the network.

The schedule of events demanded that event 1 commence despite high seas and winds that presented unfavorable noise conditions for acoustic communications. During the event, the ship bridge reported seas up to 12 feet. The undersea vehicle operated near the sea surface which disadvantaged the vehicle as a receiver, primarily because of high noise levels, but also because of the deep mixed layer and the aspect-dependent mounted transducer.

The ship could communicate with Nodes 20 and 35 with Seaweb utility packets, but not with data packets. Seaweb administrators rerouted network traffic around 20, but only partially rerouted around 35. Meanwhile, plans for the deployment of a third racom buoy to back up the one functioning racom unit were developed. High seas would prove to stall this deployment until day four of experimentation.

When the grid was deployed the network relied heavily on the left and center columns of nodes. Both were routed straight down to the gateway. The right column was routed in as leaf nodes. Because of lack of confidence in Node 20, the southernmost portion of the grid was rerouted. As well, Nodes 35 and 47 were not yet operating properly. Therefore, in hindsight, the northeastern portion of the grid was deemed inoperable for the day of operations and testing.

The first message sent by the undersea vehicle was via Node 42 in the most northerly section of the grid. The ship sent a reply, but a return receipt was not received at the ship. The undersea vehicle was deemed to be a disadvantaged receiver when operating at shallow depths, especially in high seas where ambient noise in the 9-14 kHz Seaweb band is dominated by wind and sea-surface turbulence. Compounding this was the strong and deep mixed layer. When the undersea vehicle operated at lower depths it would experience better communications. Despite adverse conditions, data packets from the undersea vehicle were successfully transmitted to the ship via cellular Nodes 42, 24, 22, 22, 19, 19, 21, 21, 21, and 22, consecutively. All activity was logged and time-stamped by the Seaweb server on the ship.

2. Day Two

On Day 2, the network seemed to have been hindered by more than just the 12-foot seas and 30-kt Northerly winds. Due to an apparent malfunction within Node 25, the majority of the network could not be accessed. At the time, it was unclear what had happened to Node 25, other than the fact that it was not operating properly. In retrospect, all evidence indicates that Node 25 was lost to trawling on this day. As seen in Figure 20, without Node 25, the entire northern portion of the grid was inoperable. In order for communications to resume, it was necessary to reroute around 25. As well, the ship's moor had become unstable and the ship was moving within the buoy box causing Free Wave radio connectivity issues with the racom gateway buoy.

During Day 2, messages arriving from the undersea vehicle did not reveal the Seaweb cellular address as intended, thus thwarting the intended response messaging in the Seaweb 2004 session layer protocol. This cellular address is embedded in the Seaweb header utility packet and a simple Seaweb modem firmware change would be required to extract it. Had the schedule permitted, end-to-end connectivity testing would have revealed this problem before experiment commencement. A workaround involved reprogramming the undersea vehicle to explicitly declare the cellular address in the body of transmitted messages. The network issues experienced this day allowed only one data packet from the undersea vehicle to be transmitted to the ship via cellular Node 22.

3. Day Three

Day 3 brought successful bidirectional communications. The ship communicated successfully with all deployed nodes in the grid with the exceptions of Nodes 23 and 25. Both nodes were thought to have failed, and in fact were probably trawled out. Therefore, a plan for replacement was developed. Upon replacement of the repeater nodes, the second ship was to deploy an additional racom buoy in the same general area as the others as a backup gateway node, and if time permitted, the ship would also use a telesonar deck unit for direct interrogation and reprogramming of Nodes 37, 38, 39, 40, 41, and 42. It is important to note again, that if time and weather had allowed, direct interrogation and reprogramming of nodes would have been completed days earlier during end-to-end testing.

During Day 3 numerous routing and performance issues in the grid that would normally have been corrected prior to the exercise were resolved with the aid of the second ship. Rerouting was very successful. At the end of Day 3 only four nodes were unavailable due to a lingering issue with Node 36. Data packets from the undersea vehicle were successfully transmitted to the ship via cellular Nodes 17, 17, 20, 18, 18, 17, 17, 20, 19, 19, 17, 20, 26, 44, 44, 44, 27, 31, 47, 48, 48, 49, 48, and 48, consecutively.

4. Day Four

Finally, on the fourth day of the experiment, mild winds and seas allowed the second ship to deploy the additional racom buoy in the vicinity of the other two gateways as a backup gateway node. Racom buoy G2b was left in the water because it remained functional in terms of the FreeWave link and as a telesonar receiver, and because recovering it might have endangered the other nearby racom buoys. The second ship attempted to recover Node 23, but actuation of the acoustic release did not result in the surfacing of the node. This could have been because of the node depth, or because of the trawling of the grid. Due to time constraints, recovery of Node 25 was not attempted. Node 55, the replacement for the two nodes, was deployed and successfully assimilated into the grid. Two trawling vessels were observed operating within the Seaweb grid during Node 55 deployment, further supporting suspicions of trawling down the center column of nodes. It is believed that Nodes 23 and 25 were both removed from the grid during earlier trawling.

Communications were further improved by the lower undersea ambient noise during day four of testing, but issues with Nodes 32 and 33 prevented traffic flow from Nodes 34 and 35 north. Data packets from the undersea vehicle were successfully transmitted to the ship via cellular Nodes 45, 26, 28, 24, 20, 44, 24, and 20, consecutively.

5. Day Five

Day 5 brought the return of high ambient noise levels with increasing winds and seas. The ship communicated successfully with all deployed nodes in the grid. Node 55 deployed on Day 4 was functioning, but with weak performance. On Day 5 no packets were sent to it or from it, therefore it was considered out of the network. Because Nodes 23, 25, and 55 were concentrated in one particular area, an area with somewhat more bathymetric gradient than elsewhere in the grid, it was erroneously hypothesized at the time that this telesonar dead zone was a result of seafloor properties.

Minor maintenance on the grid took place on Day 5, but the northern portion of the left and center columns were problematic. Data packets from the undersea vehicle were successfully transmitted to the ship via cellular Nodes 19, 28, 43, 24, 24, 43, 43, 55, 44, and 43, consecutively.

6. Day Six

Calmer conditions prevailed on Day 6. Winds were approximately 10-20 kts and seas 2 to 4 feet with swells of 6 to 8 feet. The ship was moored just 2 nautical miles from the racom buoys and maintained continuous FreeWave connectivity with the deployed gateways. Network rerouting was at a minimum and it appeared as if the network was in working order, with the exception of the center column on the 300-meter contour. The entire left column was functional. Node 55 also appeared to be in working order. Data packets from the undersea vehicle were successfully transmitted to the ship via cellular Nodes 35, 35, 34, 34, 24, 21, 24, 26, 24, 20, 44 and 43, consecutively.

7. Day Seven

The weather provided calm conditions with winds from 10 to 15 kts and seas of 2 to 4 feet with swells of 4 to 6 feet. Only two minor network changes were made, and the center column of nodes still exhibited problems. Although the undersea vehicle operated in the domain of the Seaweb grid only briefly this day, data packets were successfully transmitted to the ship via cellular Nodes 30, 28, 26, 22, 21, and 24, consecutively.

8. Day Eight

By the end of the experiment, the deployed Seaweb grid of 3 racom buoys and 40 repeaters were fully functional, save for Nodes 23 and 25. The 7 nodes composing the original pilot grid (Seaweb Nodes 11-17) had been deployed 16 days and remained operational with good battery readings. The remaining nodes forming the rest of the operational grid had been deployed 15 days with good battery readings. The ship personnel optimized network routing and verified connectivity with the deployed modems in the grid. The successful rerouting of the network shows the feasibility and importance of future Seaweb networks to heal routing following the loss or addition of nodes. On Day 8 data packets from the undersea vehicle were successfully transmitted to the ship via cellular Nodes 24, 21, 21, 19, 19, 21, 22, 26, 28, 30, 34, 32, 30, 26, 26, 44, 19, 19, 24, 28, 29, 27, 55, 22, 32, 32, and 32, consecutively.

9. Day Nine

Interestingly, at the end of the experiment, the network routing was at its most optimal. Unfortunately the undersea vehicle did not transmit data packets during Day 9 of operations because it was operating elsewhere. After recovery of the grid and finding concrete evidence of trawling along the center column, it is obvious that had the network incorporated the center column as leaf nodes, the trawling would have had less of an impact and less rerouting would have occurred. However, the process followed by the remote administrator to reach this state of functionality is highly instructional and led to identification of several new commands that were implemented post-experiment. It is also justification for the training of additional operators for future experimentation.

C. RECOVERY

After the final day of testing, the second ship progressively recovered the Seaweb network. Utilizing the GPS locations of all node deployment locations, the second ship transited the grid and utilized a deck-box to actuate the acoustic release for recovery. Upon recovery, it became even more evident that the grid had been severely impacted by trawling. Figure 21 shows the network as routed by the Seaweb administrator in the final day of experimentation, Day 9, alongside the actual grid that was recovered. The deviations and casualties are significant and suggest that with added diagnostic features, Seaweb would be able to self-heal and overcome quite significant damage.

The following 32 repeaters were successfully recovered: 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22, 24, 26, 28, 29, 30, 32, 34, 36, 38, 39, 40, 41, 42, 43, 44, 46, 47, 48, and 49. This 80% recovery rate is notable in that it was achieved without support from a RHIB, in a strong current, and with several nodes deployed deeper than the specified operating depth of the acoustic releases. Node 29 was not found in its original deployment position. It was successfully recovered at a location 2.5 km away from its deployment station. This dislocation is thought to have occurred due to trawlers working the area. Furthermore, it is suspected that most of the unrecoverable nodes were damaged by the bottom trawling.

Even with the daily reconstruction of the network routes, it is difficult to pinpoint on which day and at what time the trawling took place. We know that two trawlers were operating within the area of the Seaweb grid throughout recovery operations, Days 11-13. The second ship had previously observed two similar trawlers in the same area on Day 3 of experimentation during the deployment of Node 55. Seven of the eight unrecoverable nodes and the one dislocated node were all from the center column of the grid. This indicated that trawling was concentrated along the 300-meter contour. This is the same area in which the trawler sightings occurred. Failure modes associated with the dislocated and unrecoverable nodes were also consistent with contact by trawls. With all of the evidence, it appears the major trawling impact occurred on or before Day 2.

No traces of Nodes 23 or 25 were found, despite ping attempts throughout the entire grid area. All 3 independent acoustic systems (telesonar modem and the pair of acoustic releases) did not respond. These nodes were problematic from the beginning of the exercise and are presumed to have been trawled in the days immediately following deployment.

Node 27 was found 2.0 km 351T away from its deployment station. The node was located through ranging and trilateration from neighboring nodes using Seaweb navigation functions. Although all 3 acoustic systems were responsive, ranging by the deck box revealed the location of the releases were 300 meters away from the telesonar modem, indicating the release had separated from the modem. Failure of the float to surface following successive burn commands to both acoustic releases indicates the float had been severed.

Node 29 was successfully recovered, although it was found 2.5 km 349T away from its deployment station. The telesonar modem was undamaged but showed traces of red and green paint. This telesonar modem carried sediment indicative of being dragged along the bottom.

Node 31 was found 2.2 km 262T away from its deployment station. All 3 acoustic systems were responsive; therefore failure of the node to surface following burn commands to both acoustic releases indicates the float had been severed. This node was found to be collocated with Node 33, suggesting these nodes had perhaps been hauled up, floats severed, and the modems and releases discarded overboard.

Node 33 was found 4.7 km 181T away from its deployment station. All 3 acoustic systems were responsive. It is thought that the sub-surface float was severed from this node as well.

Node 35 was found at its deployment station, however it did not surface. Loss of the float would have caused the modem to rest on the seafloor and possibly bury in the sediment. A collapsed posture is consistent with the poor acoustic performance of this node during the experiment. Node 37 was also found at its deployment station, but did not surface.

Node 45 did not respond through either the telesonar modem or acoustic releases. This is the only unrecovered node not belonging to the center column. Therefore, its failure is not necessarily attributable to trawling. This node was in water deeper than the 300-m rating of the acoustic releases, but there is no direct evidence to indicate failure of the releases.

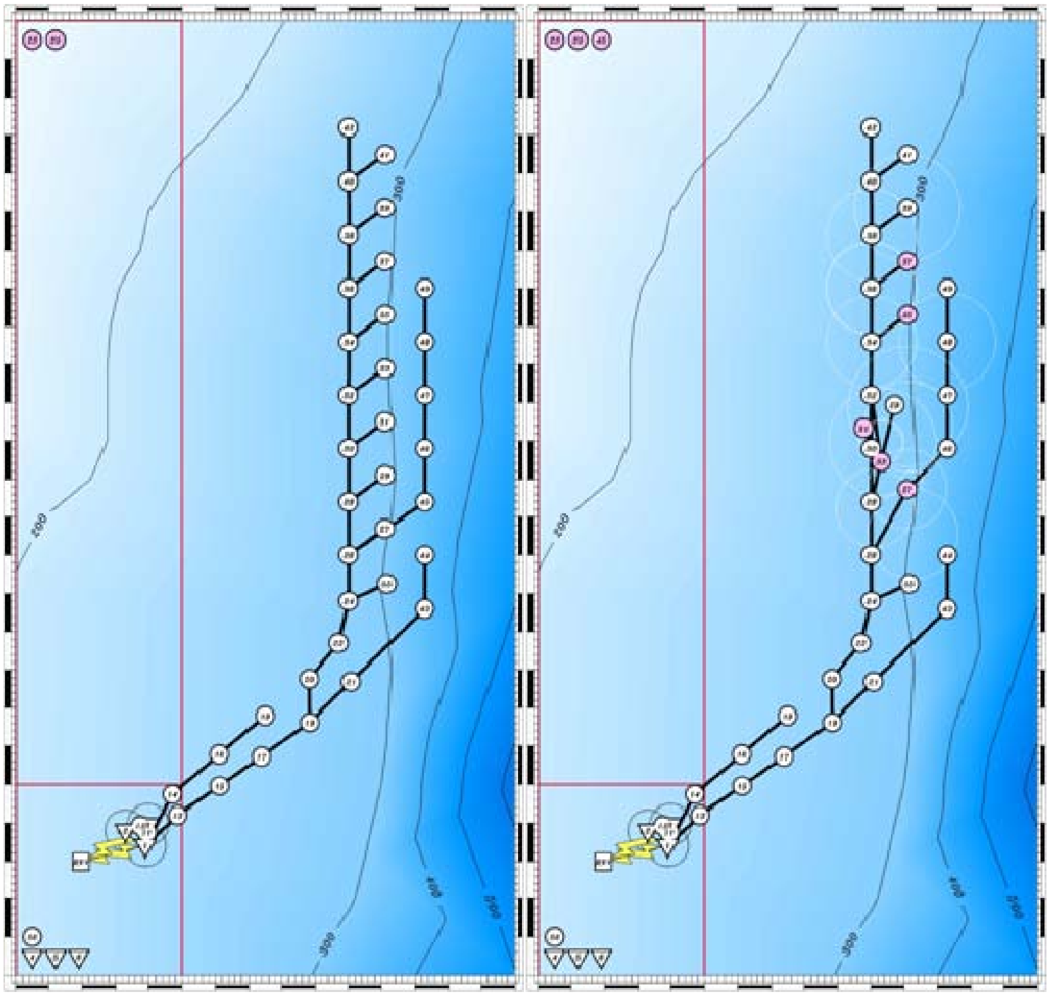

Figure 21. The network routing on the last day of the experiment, Day 9, is shown on the left above in comparison to that which was recovered post-experiment, Days 10-11, on the right. The network was severely impacted by trawlers. The trawlers were seen within the area on three different occasions. Performance was greatly impacted by this major disruption, but reliable 800 bits/s communications were still maintained.

VII. SEAWEB 2004 PERFORMANCE

Seaweb quality of service is limited by low-bandwidth, half-duplex, and high-latency telesonar links. Poor propagation conditions and elevated noise levels contribute to occasional network outages and corrupted data packets [9]. Seaweb 2004 performance is quantified by the overall message throughput, latency of network packets, and the contributing factors for the dropped messages.

A. MESSAGING SUCCESS

Throughput is defined as the amount of information transmitted through a communications link. Factors such as bandwidth, errors, congestion, and the transmission medium properties affect the total throughput values. For this analysis we discuss throughput in terms of overall messaging success at the transport layer, i.e., the total number of network packets successfully transmitted through the network and received error-free at the destination node.

Several types of messages were sent over the course of the Seaweb 2004 experiment. Examples of the kinds of messages were own vehicle positions, command and control messages, general network health monitoring, node-to-node ranging, and network routing. Regardless of type, each data packet sent through the Seaweb server is designated with a network packet sequence number and a timestamp. The sequence numbers range from 1 to 255, and then cycle back to 1. By tracking the sequence number along with the associated timestamp, we are able to count the number of packets successfully transmitted and received by the ship and by the undersea vehicle. Limiting our analysis to traffic between the undersea vehicle and the ship, the messaging success is compiled in Figure 22.

Initially the Seaweb administrator exercised the Seaweb pilot network through a FreeWave radio link between the ship and the deployed racom buoy. All 7 pilot grid repeater nodes were found to be fully functional. The testing performed included data telemetry of 1-kilobyte test packets at information bit-rates of 300 and 800 bits/s. Testing also involved remote selection of transmit power levels, node-to-node acoustic ranging, node-to-multinode ranging, and networked interrogation of modem diagnostics. As a result of those tests, the baseline data rate for Seaweb 2004 was increased from 300 bits/s to 800 bits/s, and the baseline transmit power level was set to 6 dB less than the maximum power available. Successful communications with these parameters at ranges exceeding 6 km provided confidence that the 3-km node spacing would reliably serve the needs of the exercise. The overall results support this conclusion as well.

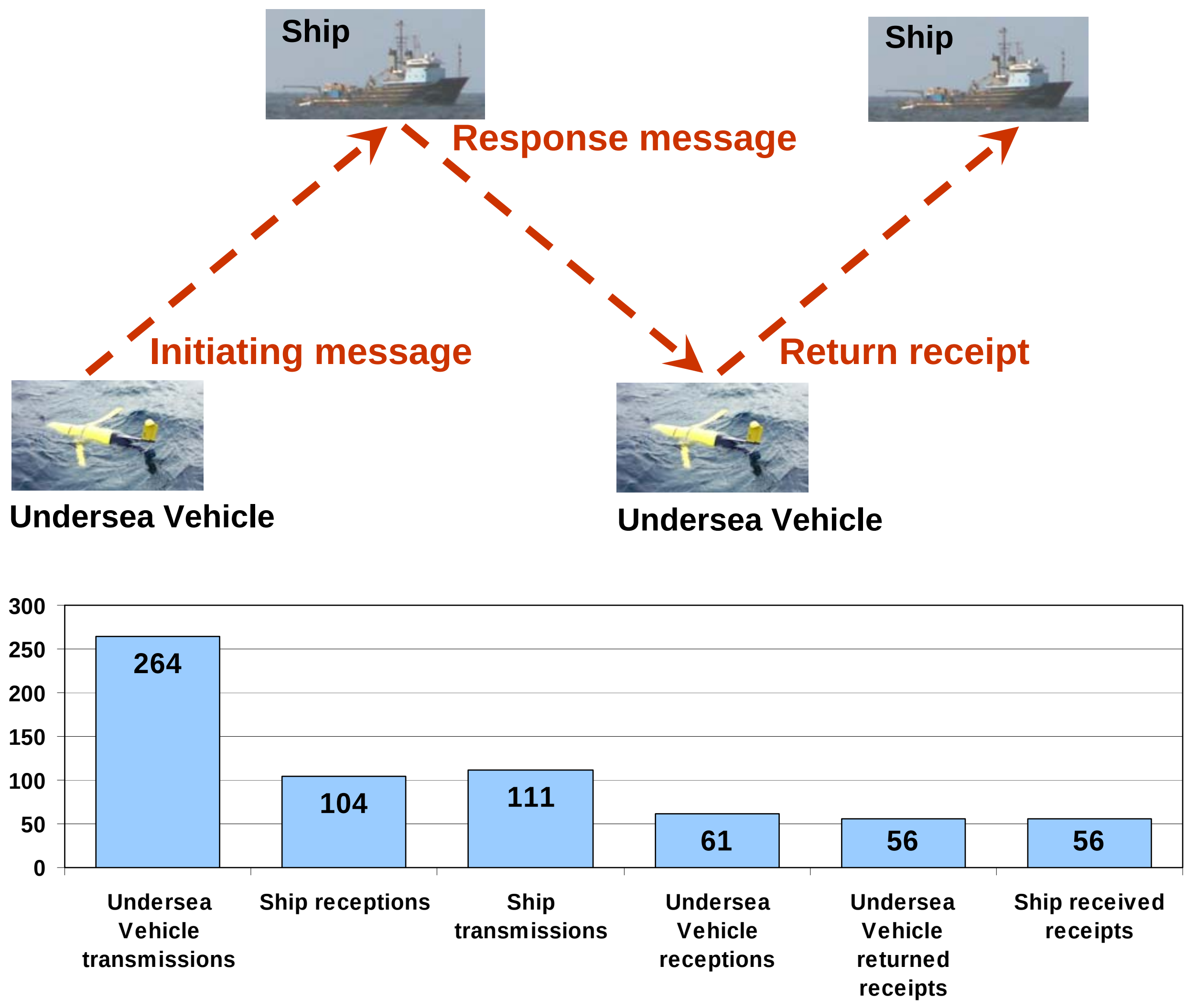

Figure 22. The total amount of messages sent from the undersea vehicle and the ship as well as those received onboard the undersea vehicle and ship. One hundred and sixty messages were unsuccessfully received onboard the ship and fifty messages were not received onboard the undersea vehicle. Section C identifies the reasons for these dropped messages.

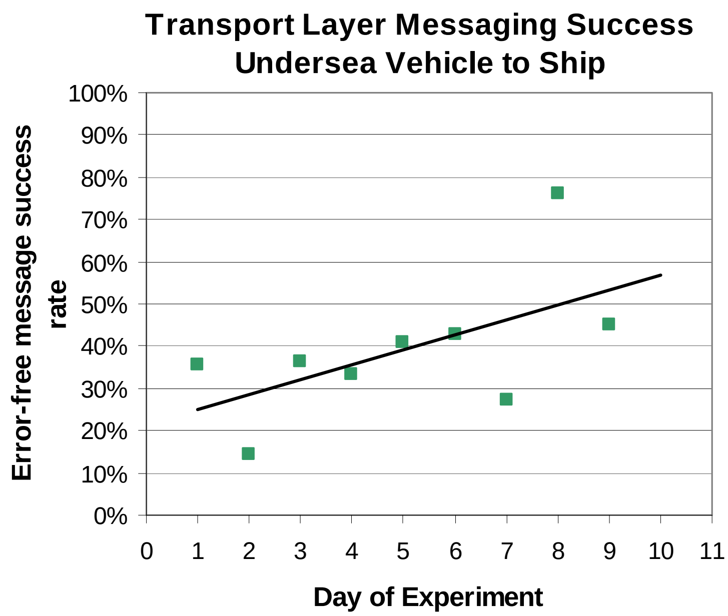

Figure 23. Messaging success from undersea vehicle to ship also tended to increase on a daily basis. As the experiment progressed, sensitivity to the issues of proximity and aspect of the undersea vehicle relative to the cellular node increased messaging success.

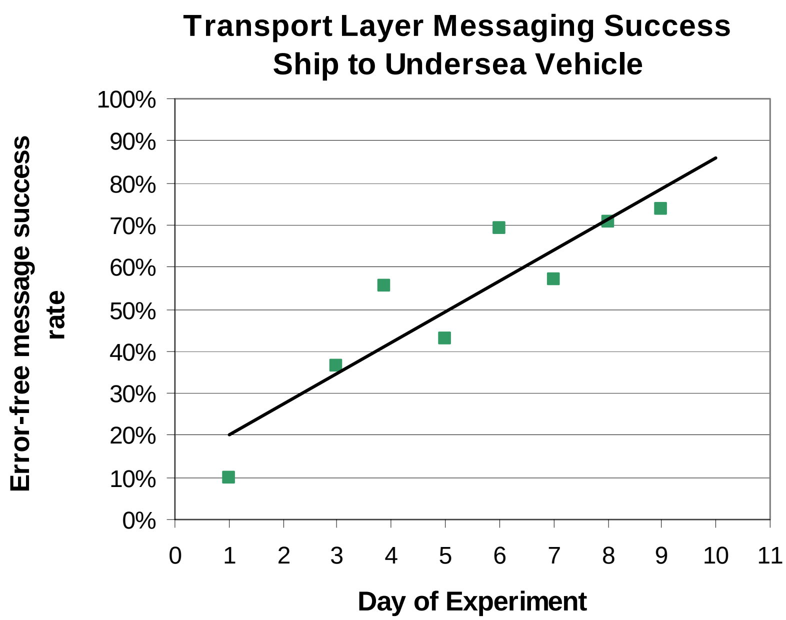

Figure 24. Messaging success from ship to undersea vehicle increased over the course of the experiment. This is attributed to decreasing ambient noise levels within the environment, troubleshooting and rerouting of the network, and increased operator proficiency.

During the days of experimentation, the Seaweb administrator did not exercise the grid in a rigorous manner. As the goal of the experiment was bidirectional communications between the undersea vehicle and the ship and the communications protocol established that the surface vehicle would wait to receive a message prior to sending one, the operators were compelled to keep the network available to the undersea vehicle. Network packets were sent to various nodes within the grid only in response to an issue encountered with that node or one around it, or during time periods when the undersea vehicle was known to be operating elsewhere.

Daily transport layer success rates to ship and undersea vehicle are compiled in Figures 23 and 24, respectively. The trend shows steadily improving performance over the course of the experiment, especially for communications to the undersea vehicle. Progressively increased messaging success to the undersea vehicle is attributable to the following factors. The established communications protocol favored the messaging from the ship to the undersea vehicle. The ship knew from which cell the undersea vehicle transmitted and used this information to return a response message prior to the undersea vehicle leaving that cellular area of the grid. As the undersea vehicle maneuvered within the domain of the grid, the ship was able to observe behavior and improve performance of the various nodes in the grid. These optimizations, of course, should have occurred prior to the experiment with end-to-end testing as had been planned. As well, the ambient noise within the operating environment decreased during the experiment, as supported by Figure 6.

Not only did the testing and correcting by the Seaweb administrator increase messaging success to the undersea vehicle, it also increased messaging success from the undersea vehicle as well. After discovering the loss of Nodes 23 and 25, the ship was able to reroute network traffic around that area, thus significantly improving the overall performance of the grid. The undersea vehicle also did not exercise the grid uniformly. It tended to use the southernmost portion of the grid more than the northern portion. Due to the nonsystematic fashion in which nodes were selected as communication access points, it is difficult to determine the relative effectiveness of all network nodes.

B. LATENCY

The automatically generated timestamps in the Seaweb server archive were used to calculate latency times. The latency times are divided into 3 analysis categories: ship to undersea vehicle, undersea vehicle to ship, and ship to fixed node. Latencies are then plotted as a function of range. Ranges are calculated by using the distance from the gateway buoy to the network node as addressed by the administrator or as used as a communications access point by the undersea vehicle. As expected, latency increased linearly with range. In order to support effective bidirectional communications, it is imperative that latency times, much larger than terrestrial counterpart systems, be kept to a minimum. Latency times will decrease with the planned implementation of automatic "best-route" routing algorithms in the future.

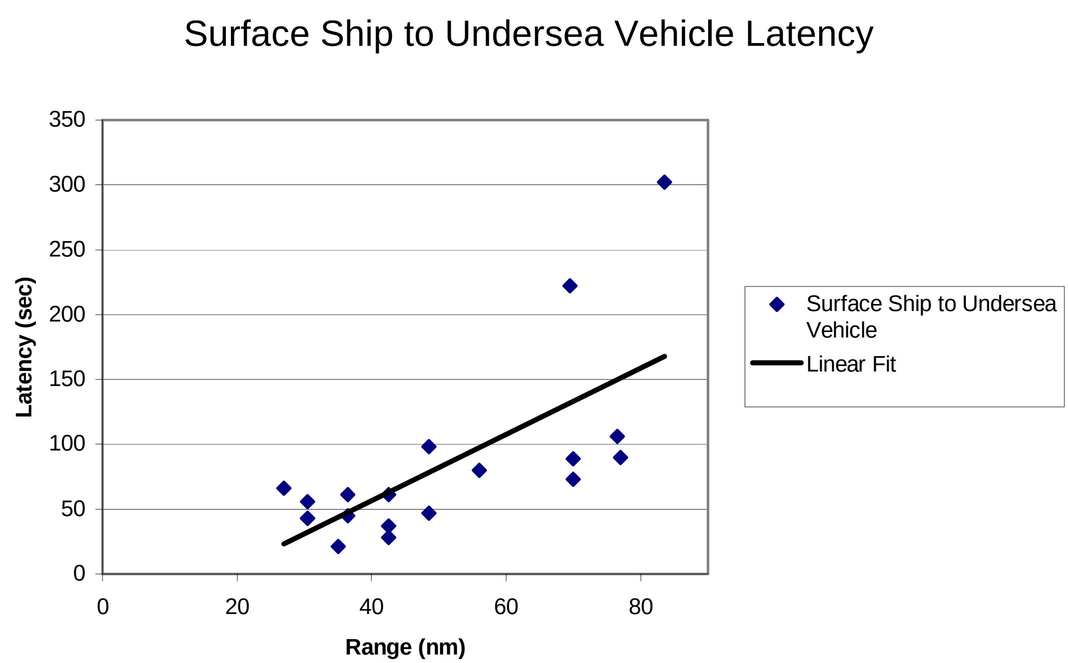

Figure 25. The ship to undersea vehicle latency is calculated using the timestamps entered into the database archives by the Seaweb servers. This is a latency that includes the handshaking process between all nodes in the route from source to destination.

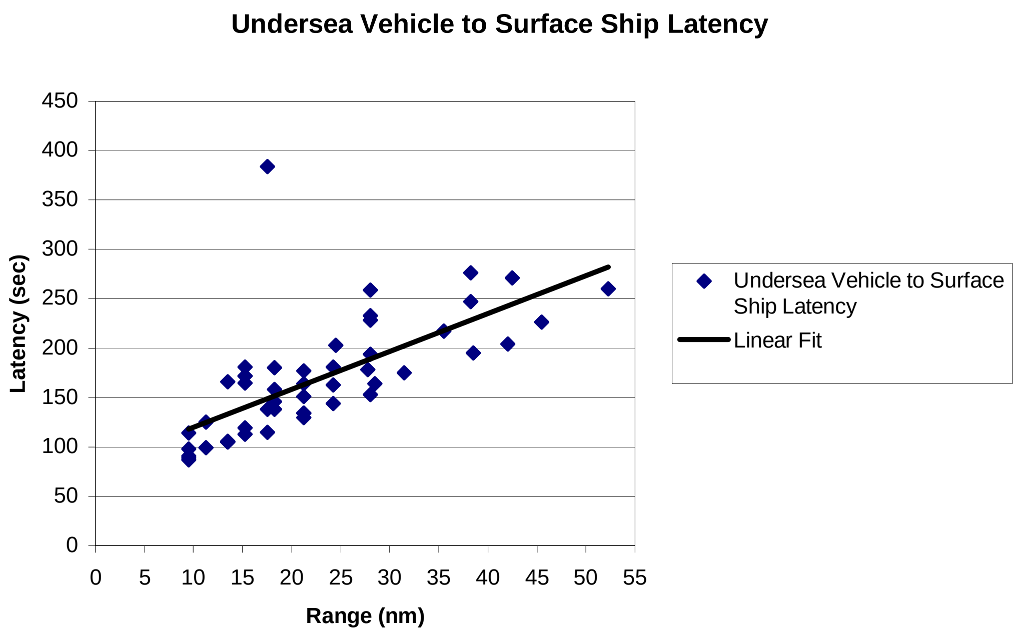

Figure 26. The undersea vehicle to ship latency is calculated using the timestamps from the database. The range is determined by using the distance from the cellular node the undersea vehicle used to transmit the data packet to the ship and back. The distance from the undersea vehicle to the node is neglected.

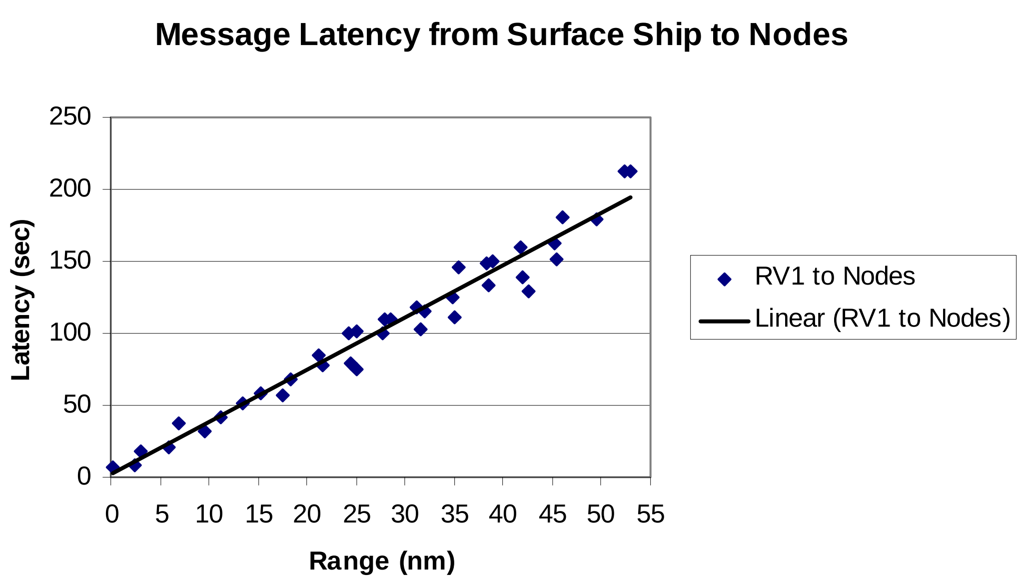

Figure 27. Nodal latencies are calculated in the same fashion as those of the ship and undersea vehicle. These transmissions were always between fixed locations which explain is why they exhibit a more linear fit.

C. DROPPED MESSAGES

A dropped message is defined as a message that was transmitted by a source node and not received by the intended destination node. Some of these dropped messages are the result of human interaction with the system, while most are due to various engineering issues associated with the present Seaweb system operating with a mobile node. The sequence number and specific timestamp enable us to track each network packet from source to destination. A sequence number that is not correctly received is analyzed and the dropped message is attributed to one of many causes based on the logged link diagnostics.

In this analysis, transmissions are separated into those transmitted by the undersea vehicle and those transmitted from the ship. These data are compiled and charted in Figures 28 and 29, with a view of overall performance at the transport layer. The undersea vehicle sent considerably more network packets as a result of the established Seaweb 2004 session protocol. The following is a discussion of the categories of dropped messages identified during Seaweb 2004.

Several messages were dropped because of link impairments. These categories include link unavailability (RTS timeout), low signal-to-noise ratio (SNR), and data failure problems. For this analysis, the low-SNR category captures most physical-layer degradations caused by the combination of low signal (i.e., poor propagation) and high noise.

Request-to-Send timeouts occur when Node A initiates the link-layer handshaking procedure with Node B, but Node A does not receive a Clear-to-Send message. When this happens, Node A will continue to send 9-byte RTS packets up to a preset number of attempts programmed by the administrator. Upon time-out, the packet is dropped.

Even when the RTS/CTS handshake is successful, low-SNR errors occur when the link budget is not adequate for error-free reception of the data packet. If Node B cannot demodulate the data packet correctly, it produces a low-SNR detection error and drops the network packet.

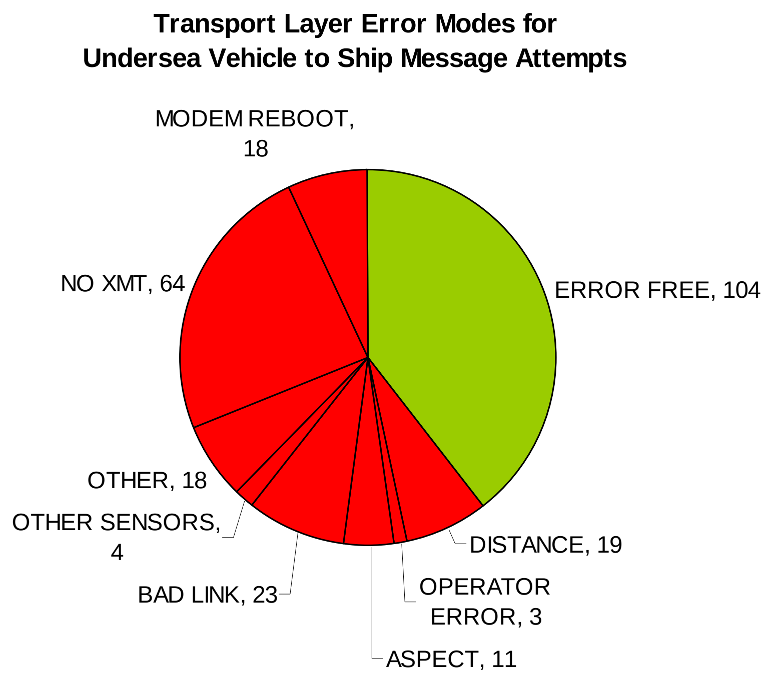

Figure 28. The 160 dropped messages not received successfully by the ship are attributed to the various factors listed in this chart.

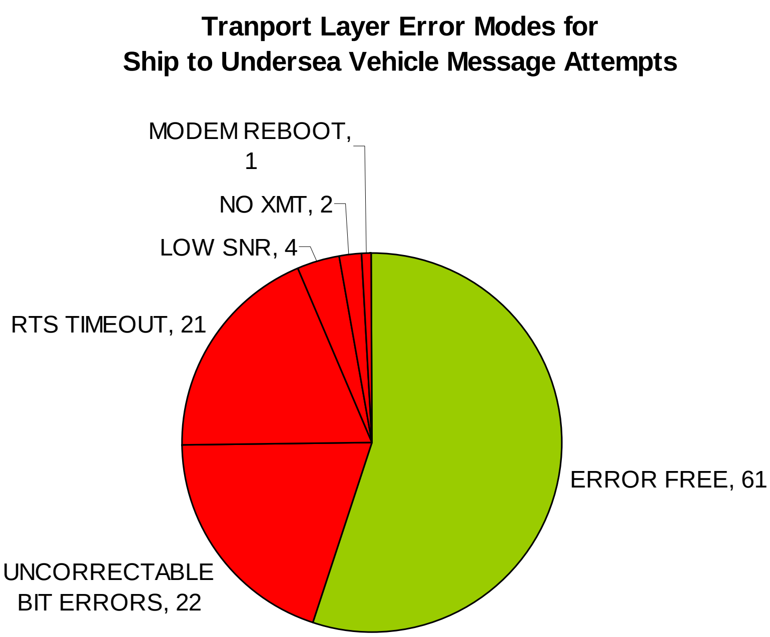

Figure 29. The 50 dropped messages not received successfully by the undersea vehicle are attributed to the various factors listed in this chart.

Data Failure error messages cause packets to be dropped when Node B receives the data packet, assumes it was correctly transmitted, and upon demodulation realizes the data string is corrupt. Normally in the hand-shaking procedure Node B would send a Selective ARQ message to Node A upon receipt of the corrupt packet. If Node A does not receive the SRQ within the allotted time period, it does not resend the data packet, thus producing a dropped message.

Hardware issues caused dropped messages when the racom buoy had to be rebooted and when no transmit (No XMT) errors occurred. If a network packet was in the process of being transmitted, the reboot would cause the packet to be dropped since it never made it from the ship to the racom gateway buoy and henceforth to the addressed node or undersea vehicle.

Transmissions originating at the undersea vehicle were more prone to being dropped since the vehicle often did not have a good sense of where it was relative to the nodes in the grid. Physical limitations such as distance from the node used as the communications access point, vehicle aspect to the node, a bad link between other nodes within the grid that are being used to transmit through to the destination, and other sonars operating within the water-space around the network caused messages to be dropped. Because Seaweb is currently operated with man in-the-loop, operator error sometimes adversely influenced messaging success.

Overall, most of the issues influencing Seaweb 2004 message delivery can be resolved by improving the engineering of the system with mechanisms such as link automatic rerouting and modem reboots. Others, such as operator error and other sensors operating within the same water-space, need continued testing and development.

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VIII. FUTURE IMPROVEMENTS

The 5 by 20 nautical mile Seaweb 2004 grid of 40 subsea nodes was the largest wide-area acoustic network ever to be demonstrated. As with any experimental implementation, there is room for improvement with equipment, hardware, and personnel. Recommendations follow.

A. NAVIGATION POSSIBILITIES WITHIN THE SEAWEB GRID

A significant lesson learned is the importance of the undersea vehicle awareness of its own position within the grid as a prerequisite for effective operation as a mobile node. This lesson has led to the dual use of the Seaweb fixed grid as an undersea constellation of reference points for GPS-like navigation. A series of 3 Seaweb engineering experiments in 2005 (May, July, December) are developing that navigation capability as a Seaweb function. Seaweb navigation and Seaweb communication are therefore becoming highly interdependent functions, especially so for future mobile connectivity requirements. [24, 25]

B. MOBILE CONNECTIVITY

Implementing mobile connectivity will enable seamless communications with undersea vehicles in the Seaweb domain. In order to achieve this, cellular addressing needs further development to support automated mobile connectivity. Seaweb diagnostics must be improved and further automated. Finally, a true ping command that would trace the outbound and inbound routes would aid in post-experiment exercise analysis.

C. ROUTING

Network routing and initialization was done manually during this experiment. Seaweb of tomorrow is an ad hoc network which will autonomously establish preliminary connections. A procedure is required for performing initialization and maintaining connectivity to all nodes within acoustic range. During the initialization process, the nodes would create their own neighbor tables to include the quality of the acoustic links between themselves and their neighbors. A master node would collect this information to determine the best routing configuration. By utilizing an adaptive routing algorithm, an increase in robustness would allow the network to react to changing channel conditions without interruption in communications. Each time the network is used, the link parameters exercised along the route would be reported, thus allowing the master node to efficiently monitor network health [16, 18].

Neighbor Sense Multiple Access (NSMA) is a network layer process that passively monitors Seaweb traffic. After assessing the communications status of neighbor nodes, a node with a message to be transmitted avoids unnecessary collisions by delaying new dialog until the neighbor node is finished, or it transmits. This is an added measure for collision avoidance. NSMA was successfully demonstrated at sea in a February 2005 Seaweb experiment [16].

In future experiments, routine testing of all routes within the network should take place on a daily basis. This would provide a baseline from which network reconstruction could be derived. Without daily verification of the network health, it is difficult to specify the time-frame in which a node stopped working and/or was trawled.

D. RACOM BUOYS

In order to implement Seaweb as a fixture for underwater communications, it is imperative that an improved design for racom buoy rugged handling be designed. Until then, waiting for calm seas is necessary for successful recovery. The radar reflector should be eliminated, a taller prow designed, flush GPS and Iridium antennas added, and an improved transducer cable developed. Racom buoy wet-end survivability must be addressed as well. Utilizing the military version of the FreeWave radio modems operating at 138 MHz and supporting up to 50-nautical-mile line-of-sight connectivity vice the shorter range 900-MHz commercial FreeWave modems would increase stable connectivity for communications. In addition, efforts are underway to produce an energy-harvesting, mooringless racom buoy capable of maintaining station or vectoring to a new station upon command. [3]

E. TELESONAR NODES

Seaweb capability is migrating to new telesonar modem hardware compatible with A-sized air-deployable packaging and with submarine signal-ejector packaging enabling further versatility and military applicability. The Seaweb of tomorrow will operate in multiple acoustic bands and will incorporate electronically steered directional transducers for improved transmission security (TRANSEC), link budget, energy conservation, and multiple-access performance. The new modems will incorporate channel-adaptive modulation, spread-spectrum-modulated utility packets, power control, and coherent detection.

F. SEAWEB ADMINISTRATORS, OPERATORS, AND USERS

As with any system, it is imperative that there be enough personnel trained to operate and facilitate use so that the system can physically be manned in an intelligent and sophisticated manner. With the lack of personnel qualified to manipulate the system, the individuals that were trained to administer the server became fatigued. In order to exploit Seaweb capabilities more operators need to be trained and made available during testing periods. Since future testing will involve more manned platforms, it is all the more important to recruit and train new Seaweb personnel.

It is also recommended that a shipboard sonobuoy receiver system be procured for independent real-time monitoring of Seaweb acoustic activity and ambient noise.

G. FINANCIAL SUPPORT FOR FUTURE ASW CAPABILITIES

The Seaweb underwater acoustic wide-area network shows great potential. It is consistent with the future proliferation of autonomous undersea sensors and vehicles. Not only does Seaweb show potential for communication and navigation of an undersea vehicle, but it could conceivably be incorporated as a rapidly deployable undersea wireless grid supporting communication and navigation (comm/nav) for a patrolling SSN operating at speed and depth. Seaweb demonstrated timely communications to and from the Seaweb 2004 undersea vehicle. In the current anti-submarine warfare (ASW) environment, Seaweb could act as the bridge between terrestrial communications and the underwater battlespace. It could potentially afford submarines the ability to communicate in stride without surfacing. In order for this to come to fruition, the Navy needs to invest resources in the procurement and further development of Seaweb capabilities. Seaweb enables new concepts of operations involving autonomous distributed systems, and it integrates existing systems into that future architecture.

IX. CONCLUSIONS

The Seaweb architecture anticipates the inevitable proliferation of future undersea sensors. Seaweb is a technology motivated by the need to network these distributed sensors and communicate with them through gateway nodes. It is a malleable architecture that can be matched to the characteristics of the particular ocean environmental conditions and mission at task.

The Seaweb 2004 experiment demonstrated a 5 by 20 nautical mile grid, the largest undersea network to date. The network maintained a reliable 800 bits/s physical layer while demonstrating effective collision tolerance. As well, rerouting healed the network following severe impact by trawling within the first few days of testing. During the experiment less than 25% of the overall telesonar node battery capacity was consumed. The undersea vehicle, while a disadvantaged receiver, maintained bidirectional communications through the low-power distributed grid.

The overall performance of Seaweb 2004 was impacted by the use of an azimuthally sensitive undersea vehicle, no opportunities for end-to-end testing prior to commencing the exercise, adverse weather conditions, trawling impact, and limited operator availability. Even with the very short schedule and many challenges, Seaweb 2004 has successfully demonstrated an effective network architecture for undersea vehicle communications at speed and depth. Seaweb is scaleable, and it is consistent with future operations involving deployable autonomous sensors and unmanned undersea vehicles as force multipliers. The current operational environment requires that offboard sensors, fixed and mobile, be developed and ready for fleet use within the next few years. Seaweb stands as the most developed underwater acoustic communications network and is a new ASW capability deserving Navy investment.

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