

# NAVAL POSTGRADUATE SCHOOL Monterey, California



## THESIS

**LINK-LAYER AND NETWORK-LAYER PERFORMANCE  
OF AN UNDERSEA ACOUSTIC NETWORK AT FLEET  
BATTLE EXPERIMENT-INDIA**

by

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June 2003

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ACOUSTIC NETWORK AT FLEET BATTLE EXPERIMENT-INDIA**

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requirements for the degree of

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## **ABSTRACT**

This thesis is an analysis of the link-layer and network-layer performance of an experimental Seaweb undersea acoustic network. The objective is to statistically determine RTS/CTS handshaking and ARQ retransmission performance during the Fleet Battle Experiment-India, executed in June 2001. Many factors constrain or impair undersea acoustic communications. Analysis of a sample portion of the data reveals insights about the overall throughput, latency, and reliability of the Seaweb network.

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To LTC Martin Fair & family, I could never find the words to describe how much I appreciate your kindness and support you have offered me and my family. "Marty" you are the epitome of what a military officer should be. The future of the "Joint" U.S. Military needs more people like you. I have found a new comrade, shipmate, and friend for life, and "I like you fine, Hooah!"

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Fairwinds and Following Seas to my Father, who will be forever missed.

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## I. INTRODUCTION

Seaweb is an undersea network of acoustic modems. Telesonar signaling through the ocean medium provides digital wireless links between modem-equipped network nodes. The Seaweb network provides connectivity between undersea assets such as submarines and autonomous ASW sensors to a command center ashore, permitting target discrimination and cueing, multi-sensor coordination and tasking, and waterspace deconfliction.

Statistical analysis of a representative portion of a Seaweb data set obtained during Fleet Battle Experiment-India (FBE-I) data set shows the network is a reliable information system for future undersea warfare.

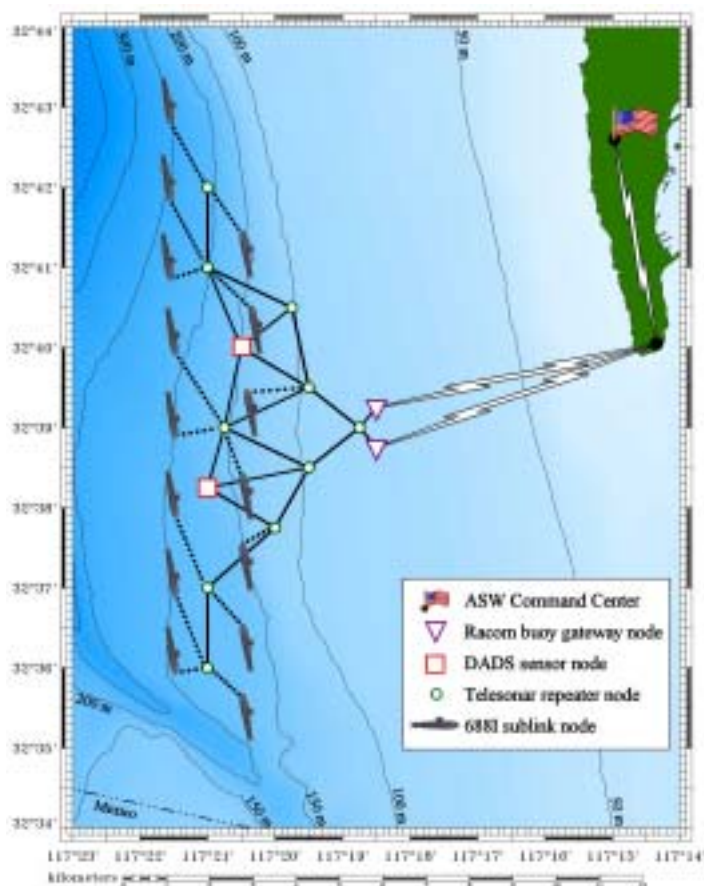


Figure 1.1 Seaweb layout

The FBE-India Seaweb network included twelve nodes at fixed seafloor stations, two moored buoys, and a fast attack submarine. The twelve seafloor nodes included two ASW sensor nodes and included two ASW sensor nodes and ten repeater nodes. The buoys were gateway nodes providing interface between radio links and acoustic links.

Figure 1.1 shows various submarine locations along with the links to adjacent repeater nodes. FBE-I Seaweb network provided the communications backbone linking the ashore Anti-Submarine Warfare Command Center (ASWCC) with the two DADS sensor nodes and a 688I submarine operating at speed and depth in the experiment operating area. An acoustic network including 10 repeater nodes and 2 Racom gateway buoys were the backbone of the network.

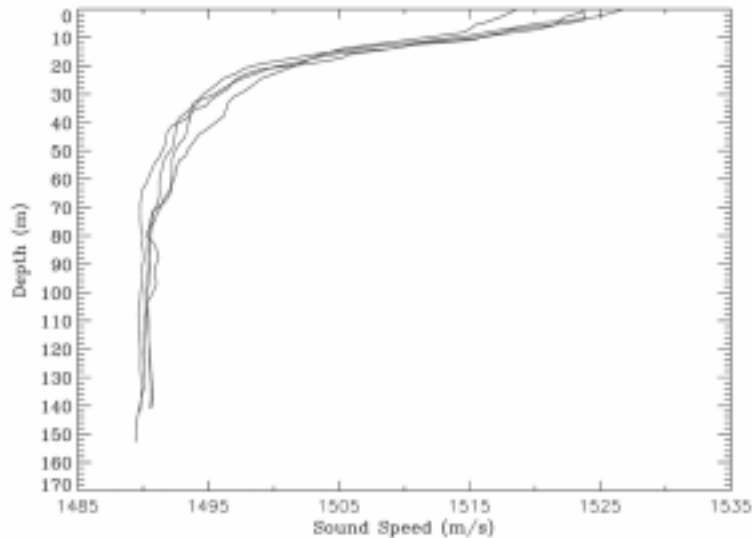
This thesis begins with a review of the many constraints and bandwidth limitations that impair communications in the ocean medium. Next is a description of the topology and hardware factors that adversely affect the Seaweb network, such as battery life expectancy, node spacing, submarine directional aspect, and submarine depth issues. Then follows a general description of the link layer and network layer. Finally, communication statistics describe the success and reliability of Seaweb performance on June 23, 2001, the most important day of the ASW component of FBE-I.

## II. CONSTRAINTS

### A. UNRELIABLE PHYSICAL LAYER

In analyzing the performance of FBE-I Seaweb, it is necessary to consider all of the factors that may have adversely affected the flow of acoustic communications through the propagation medium it traveled, the ocean. This chapter identifies the various environmental factors that make the medium so unreliable.

Testing occurred in waters 80-250 meters deep on the Loma Shelf in a region west-southwest of Point Loma, San Diego and north of the US-Mexico national border. Typical summer conditions existed at the site of the experiment. Sound speed profiles obtained from conductivity-temperature-depth (CTD) measurements during the experiment are shown in Fig. 2.1. [1]



**Figure 2.1 CTD Measurements**

Each line in the graph represents a once daily measurement of the sound speed profile in the oparea. The four plotted lines show that over the course of the four-day experiment, the sound speed profile was consistent and varied little. The graph shows a

strongly downward-refracting surface layer down to approximately 30 meters. This is generally good for bottom-to-bottom communications and is beneficial for node-to-node communications when the nodes are on the seafloor or, in the case of the submarine, when it is at operational depth. The transducers of the gateway nodes (moored surface buoys) were located below this layer to reduce the influence of the layer on communications. The effects of the strong refracting surface layer are known to degrade communications when nodes are at shallow depths above the layer.

Ambient noise in the teleseismic band is strongly influenced by local shipping and recreational boating, but no independent noise measurements or direct observations of shipping were attempted. [2] Proximity to the coast offered increased background noise for the FBE-I experiment. Nevertheless, the proximity of FBE-I operations to a moderately sized port suggests an elevated noise floor.

Sea state and biologics all add to the background noise in the undersea acoustic medium. When the submarine was at periscope depth, the close proximity to the surface most likely increased the receiver noise level and scattered signals sent or received by the submarine.

Environmental parameters such as local air temperature, water temperature, depth, wind speed and direction, sound-speed profiles, and sea state were measured and recorded. These conditions could have affected the performance of the network, but a detailed study has not been conducted to identify specific relationships between performance and these factors. Other factors that were not quantified are: biologics, rainfall, amount of local shipping, recreational boating throughout the area, and other human activities in the surrounding area.

Attenuation and multipath are other examples of the constraints that are present in the medium. Attenuation is the reduction of signal strength at the receiver as a result of traveling through the medium. If the signal attenuates too much, it becomes lost in the noise background and it becomes unintelligible. Multipath occurs when a signal takes different paths while propagating from a source to a destination node. A portion of the signal may travel directly to the destination, and others may bounce from the surface or bottom before reaching the destination. As a result, some of the signal will experience

delay from the longer paths to the receiver. Sound propagation through the ocean suffers from distortion and dispersion from multipath, and this effect is highly variable in shallow littoral waters such as those used for FBE-I.

## **B. BANDWIDTH LIMITATIONS**

Bandwidth is the amount of data that can be transmitted per unit of time. The FBE-I Seaweb network used a physical layer having a 300 bit/s information rate. Seaweb is constrained to a specific amount of the acoustic spectrum due to the low-pass filter property of the ocean and to the transducer transmit response. The FBE-I Seaweb operating frequencies occupied the 9-14 KHz acoustic band. The network is matched to this limitation by using formatted, brief messages that include only required and necessary information.

## **C. LATENCY**

At normal communication ranges of 2-4 km, it takes a few seconds for a signal to propagate from transmitter to receiver due to the approximately 1500 m/s speed of sound in water.

## **D. DIRECTIONAL ISSUE WITH SUBMARINE**

The submarine transducer used for acoustic communications with the Seaweb network was located in the bow. Communications to Seaweb nodes located abeam or astern suffered from reduced transducer directivity but were nevertheless successful at ranges within 1 kilometer. Communications in the rear quarter were unsuccessful on some occasions because of complete baffling of the bow HF transducers by the hull. [2]

## **E. BATTERY LIFE**

The repeaters and the gateways are autonomous devices operating on battery power with finite endurance. However, it is possible to service the network components on a regular basis to replace depleted batteries. To anticipate potential outages the

Seaweb server operator can query an individual node to determine its battery status. Also, the Seaweb server operator can issue commands to re-route traffic around weak network nodes. During the four continuous days of Seaweb operations at FBE-I, battery power was not an issue.

### III. SEAWEB

#### A. LINK LAYER

Seaweb is an undersea wireless network fundamentally based upon the telesonar link protocol. This protocol involves a handshaking process compatible with half-duplex signaling. In the link protocol concept, the initiating node transmits a request waveform with a spread-spectrum pattern uniquely associated with the intended receiver.

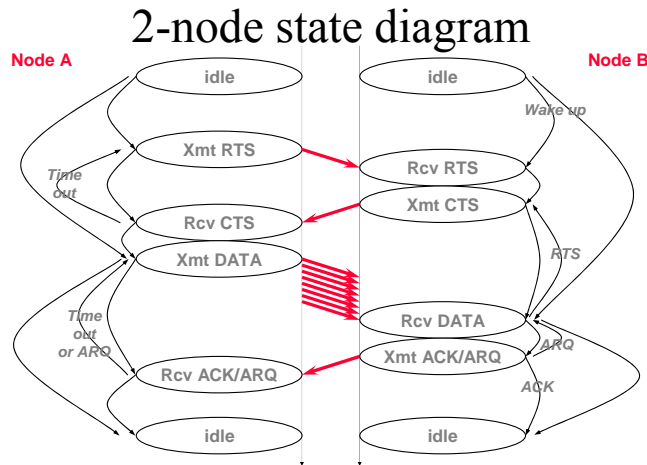
The receiver node detects the request, and awakens from a low-power sleep state. Further processing of the request signal provides an estimate of the channel scattering function and signal excess. The node then acknowledges receipt with an acoustic reply. This response specifies appropriate modulation parameters for the ensuing data packets, based upon the prevailing channel conditions. Following this handshake, the initiating node transmits the data packet(s) with optimized bit-rate, modulation, coding, and source level.

Seaweb quality of service is limited by low-bandwidth, half-duplex, and high-latency telesonar links. Poor propagation conditions or elevated noise levels contribute to occasional network outages and corrupted data packets. To minimize data loss, a medium-access-control (MAC) handshaking method illustrated in Figure 3.1 has been adopted. Half-duplex handshaking asynchronously establishes adaptive telesonar links [3].

The initiating node transmits a Request To Send (RTS) utility packet with a spread-spectrum pattern uniquely addressing the intended receiver. Alternatively, the initiating node may transmit a universal code for broadcasting or when establishing a link with an unidentified node. The addressed node detects the request and awakens from an energy-conserving state to demodulate the signal [3].

The RTS signal is processed to provide an estimate of the channel scattering function and signal excess. The addressed node then acknowledges receipt with a utility packet referred to as Clear-To-Send (CTS). This CTS reply specifies appropriate modulation parameters for the ensuing message packets based on the measured channel

characteristics. Following the RTS/CTS handshake, the initiating node transmits the DATA packet(s) at a nearly optimal bit-rate, modulation, coding, and source level. The



**Figure 3.1 Two Node State Diagram**

initiating node then waits a predefined time before it is able to accept additional incoming RTS requests. If the DATA packet is decoded at the addressed node and found to have unrecoverable bit errors, an Automatic-Repeat-Request (ARQ) utility packet is sent to the initiating node. Upon receipt of the ARQ, the initiating node repeats the DATA packet transmission. The maximum number of ARQ requests is a programmable function of the telesonar modem and is controlled by the Seaweb server operator. For this experiment, the maximum number of ARQ requests was set at three. [1]

The focus of this thesis is to analyze one day of Seaweb network traffic from FBE-I to determine the RTS/CTS/DATA/ARQ (link layer) handshaking protocol effectiveness. The purpose of conducting this analysis is to evaluate the benefits of using this handshaking protocol and to quantify the performance of the Seaweb network during FBE-I.

**B. NETWORK LAYER**

Data structures residing in the modems define the network routing for communications traffic. These routing tables are initialized for each modem by the

network administrator prior to deployment of the network by setting the values of certain S-registers. The values correspond to the node addresses of neighbor nodes that correspond to a predetermined routing topology. The S-register addresses that make up the routing table are 40-60 in hexadecimal. S-register 41 corresponds to a receiving modem node address of '1', 42 to a node address of '2', and so on.

The function of the routing table can be explained with the following example. When a modem receives a message, the message header tells the modem the final destination address for that message. The modem looks up this address in its routing table to determine which modem is to receive the message next in the route to the final destination. For example, say we have a network made up of three nodes and the routing is designed as a simple linear route. In the following example, node 1 is the "source" address and node 3 is the "destination" address.

**1 – 2 – 3**

The routing tables for the modems would be as follows:

	<b>1</b>	<b>2</b>	<b>3</b>
S41	1	1	2
S42	2	2	2
S43	2	3	3

Each column is the routing table for the modem address designated by the column header. A message is sent from '1' to '3'. '1' knows that '3' is the final destination for the message. It looks in its routing table to see that in order to send a message to the final destination of '3', it must send the message to '2'. When '2' receives the message, the message header tells it that '3' is the final destination, so '2' looks in its routing table to see that '3' is the next modem to send the message to. '3' receives the message and the header tells it that this is the final destination for the message and '3' processes the message. '2' acted as a simple repeater of the message and did not process its contents. The example routing table also permits source node '3' to network data to destination node '1' via repeater node '2'.

Through the Seaweb server, the network administrator can remotely reprogram the routing tables of a deployed network [6]. The distributed routing architecture anticipates the future implementation of an autonomously self-organizing and self-healing Seaweb network layer [7].

## **IV. FBE-I SEAWEB NETWORK**

### **A. MOTIVATION**

Future ASW forces will rely heavily upon unmanned undersea sensors and vehicles. The tactical application of these new capabilities is dependent on the data connectivity through the water and through the sea/air interface. The ASW experimentation for FBE-I focused on undersea acoustic network connectivity between the acoustic and radio frequency (RF) regimes, while incorporating existing ASW data formats (e.g., GCCS-M) into a theater tactical capability [4, 6].

FBE-I was the ninth in a series of CNO sponsored experiments coordinated by the Navy Warfare Development Command (NWDC). The NWDC Mission is to “Operationally examine innovative concepts and emerging technologies to identify advanced warfighting capabilities for further development and rapid transition to the fleet.” FBE-I was conducted in the Third Fleet Area of Operations from 18 June through 28 June 2001. The dates for the Seaweb operation were; 20-23 June 2001. The first two days (20-21 June) were focused on a wide variety of data transmissions to see what data, and in what format, would have operational utility for an undersea communications system. Note: On the second experiment day (21 June), the experiment was temporarily suspended by the FCC, due to a possible military-civilian RF frequency spectrum conflict.

The last two days (22-23 June) comprised the tactical engagement scenarios, which examined the use of the undersea network for such missions as ASW target localization through cooperative engagements by maritime patrol aircraft and friendly submarine at depth against a hostile submarine.

# FBE-I Deployment Plan

## SOCAL Littoral-ASW Oparea

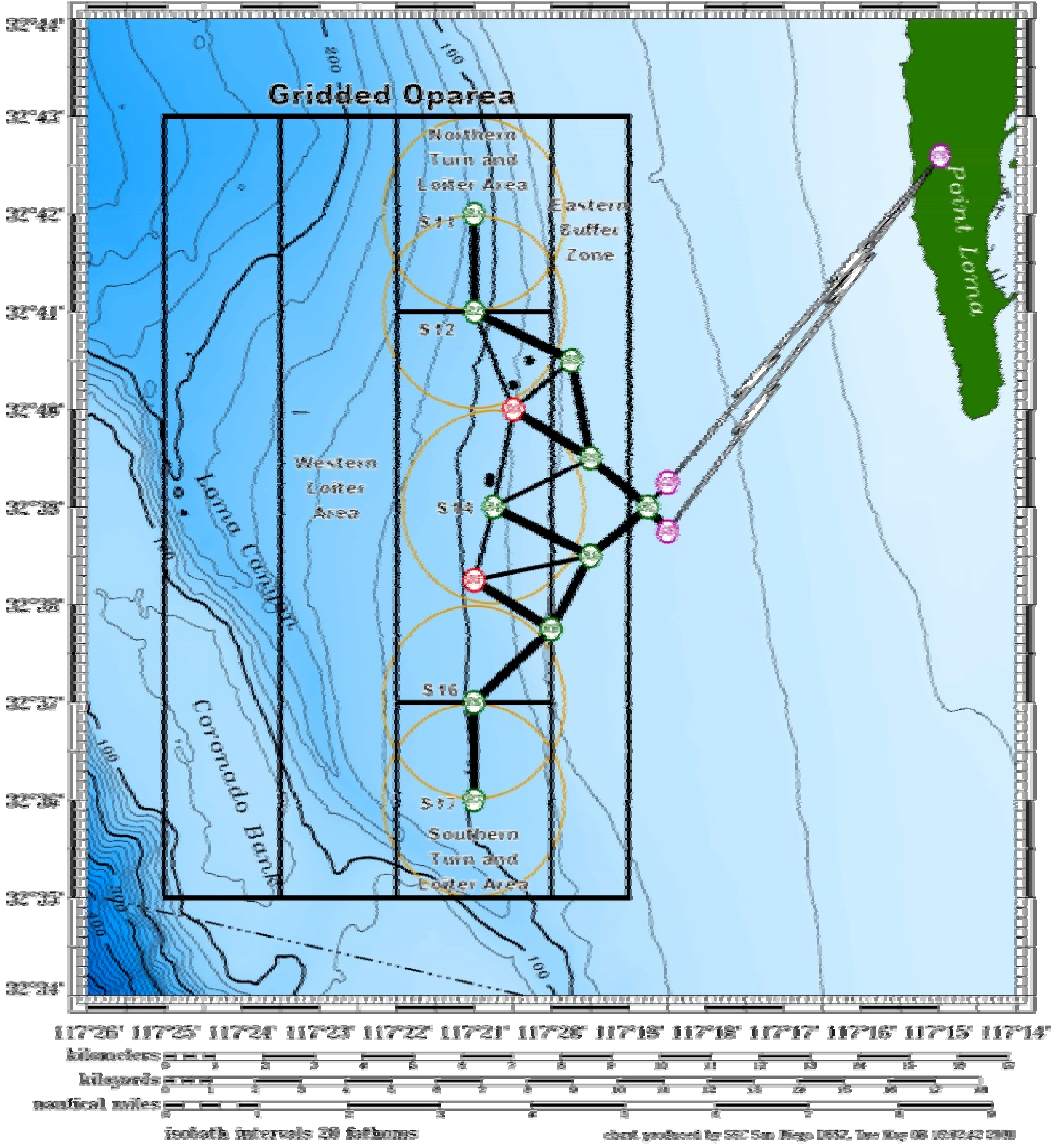


Figure 4.1 FBE-I Seaweb Deployment Topology

**B. FOCUS FOR DATA ANALYSIS**

As previously stated, the first day of the experiment was mostly set up, testing, and determining message text and formats to be used during the experiment. The second day of the experiment was suspended due to RF problems. Considering the extensive time required creating the necessary spreadsheet by manually translating the server logs the fourth day (23 June 2001) became the focus for this analysis. Even though the network consisted of 2 gateways to access the network, this analysis is focused only on the “Delta” Radio/Acoustic communications (Racom) gateway node because the “Echo” gateway was used primarily for the DADS Node’s traffic. Due to DADS requirements, the “Echo” gateway was not configured to be used for network analysis. Therefore, the data analyzed is only the acoustic Seaweb network traffic that was sent, received, or overheard by the “Delta” Racom buoy gateway node and the submarine passive Seaweb server.

**C. OPERATOR INVOLVEMENT AND LOCATION**

<b>NAME</b>	<b>ORGANIZATION</b>	<b>JOB TITLE/RESPONSIBILITY</b>
Joe Rice	SPAWARSYSCEN San Diego	TELESONAR Project Manager
Chris Fletcher	SPAWARSYSCEN San Diego	Seaweb Server Operator
Bob Creber	SPAWARSYSCEN San Diego	Seaweb server operator
Jim Hardiman	Benthos, Inc.	Representative-installation/ operations
Stephen Pelstring	NWDC San Diego	Undersea Retired Navy

**Table 1. ASW Command Center and Submarine Manning Table**

## 1. Seaweb Server

A Seaweb server resided at the ASWCC and onboard the submarine. The Seaweb server provides network administration using a graphical user interface. Network routing, health, sensor and instrument control, and data archiving are controlled by the Seaweb server [8].

## 2. Repeaters/Telesonar Modem

The telesonar modems are Benthos model ATM885 subsea modems. The frequency range of the communication signals is 9-14 KHz. Seaweb repeater nodes were

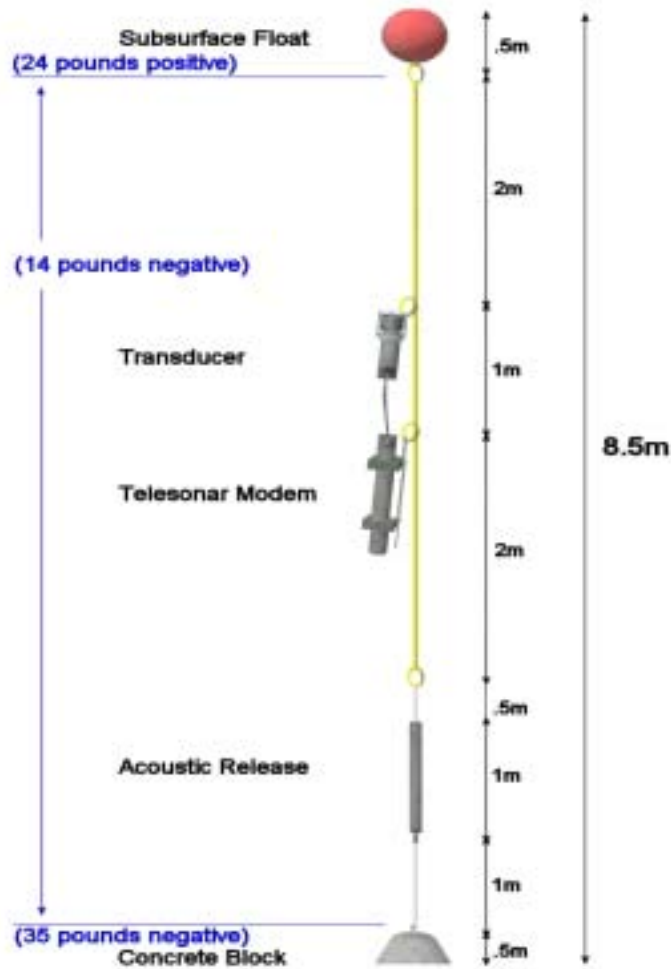


Figure 4.2 Deployed Telesonar Repeater

Deployed, as shown. The rig freefalls to the bottom when dropped from a small surface vessel.

At the completion of the mission, the acoustic release separates the rig from the anchor block and everything except the block rises to the surface for recovery. Since these modems are located on the seafloor and extend to only about 8 meters up, they do not pose a threat to submarine safety.

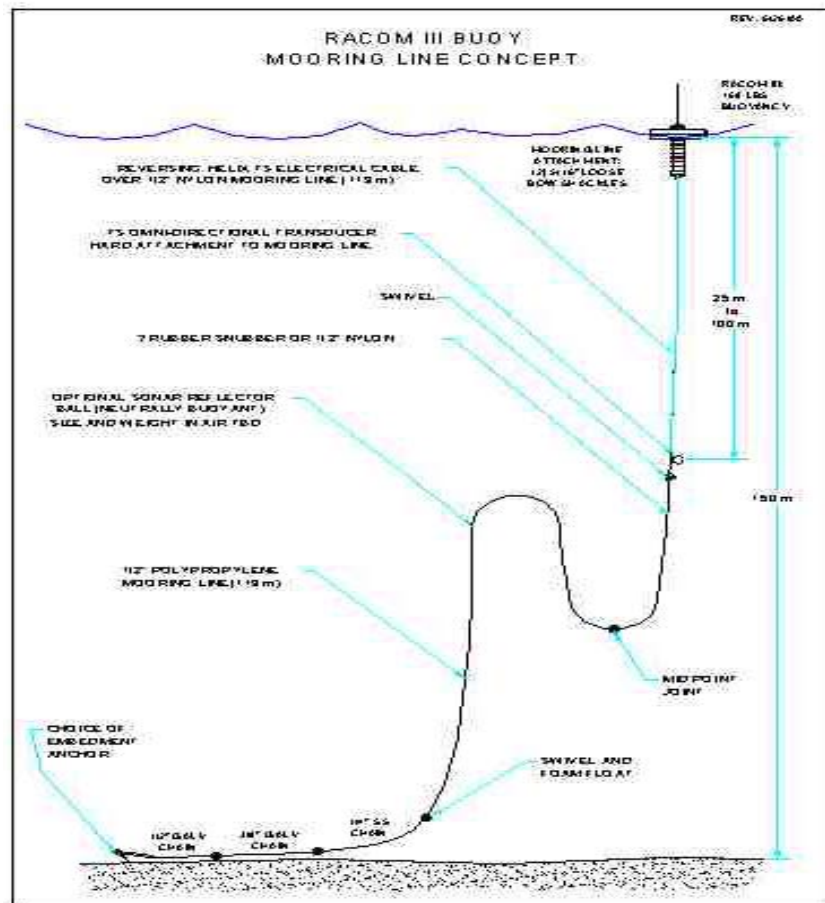
### **3. Racom Gateway Buoy**

The Racom gateway buoy is the interface between the undersea network and the Seaweb Server. The Racom can be configured with one of many communication options.



**Figure 4.3 Racom Gateway Buoy**

Communication to the Seaweb Server can be via freewave packet radio modem, Iridium satellite modem, or CDPD cell phone modem. The Racom gateways used during FBE-I were configured with the freewave packet radios. The Racom gateways are designed and constructed by SPAWAR Systems Center San Diego.



**Figure 4.4 Moored Racom**

Typically, the transducer is located at a depth of about 25 meters below the Racom gateway. Since the Racom gateway is a moored instrument, care must be taken when determining the deployment position. Since there was a submarine involved in FBE-I, the Racoms were required to be moored at a considerable distance from the submarine operations area for submarine safety. The Seaweb network topology was carefully designed around submarine safety.

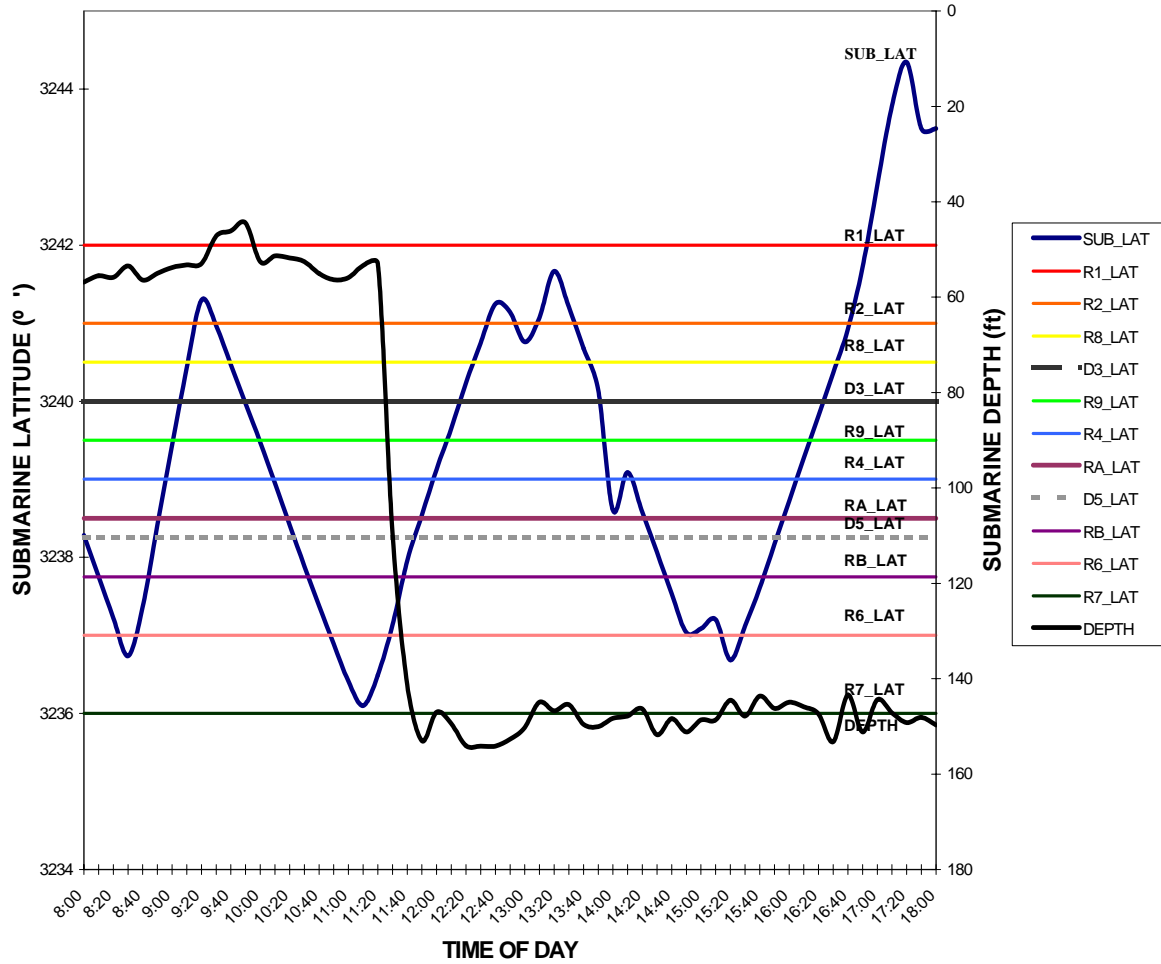
#### **D. SUBMARINE POSITION AS FUNCTION OF TIME**

In order to assess possible directional issues with the submarine transducer, a chart was produced depicting the location and depth of the submarine at ten minute intervals and the locations of fixed nodes. This chart was produced by plotting the information provided from the FBE-I Ring Laser Guided Navigation (RLGN) data; Zulu time, Latitude, Longitude, Heading, Depth, and Speed.

This chart was extremely valuable in identifying specific examples of problem data packets and categorizing unsuccessful data packets. By comparing the timestamp of the data packet in the data set to Figure 4.5 it was easy to determine if the submarine heading was facing away from the intended recipient node. However, on some occasions, the data packet was successful and was received by the intended node, even though the intended node was abeam or aft the beam of the submarine. These packets succeeded because of close proximity of the submarine to the intended node recipient.

In the FBE-I Seaweb design, the submarine cells (S nodes) were regions associated with repeater nodes. When the submarine was within one of these cells, it would assume the S address as its own. Thus, the submarine would take on a different identity as it moved from cell to cell. In 2001, Seaweb did not yet support mobile addressing, and the S addresses provided an effective workaround.

### SUBMARINE LATITUDE vs TIME OF DAY



**Figure 4.5 Sub Latitude/Depth/Time Chart**

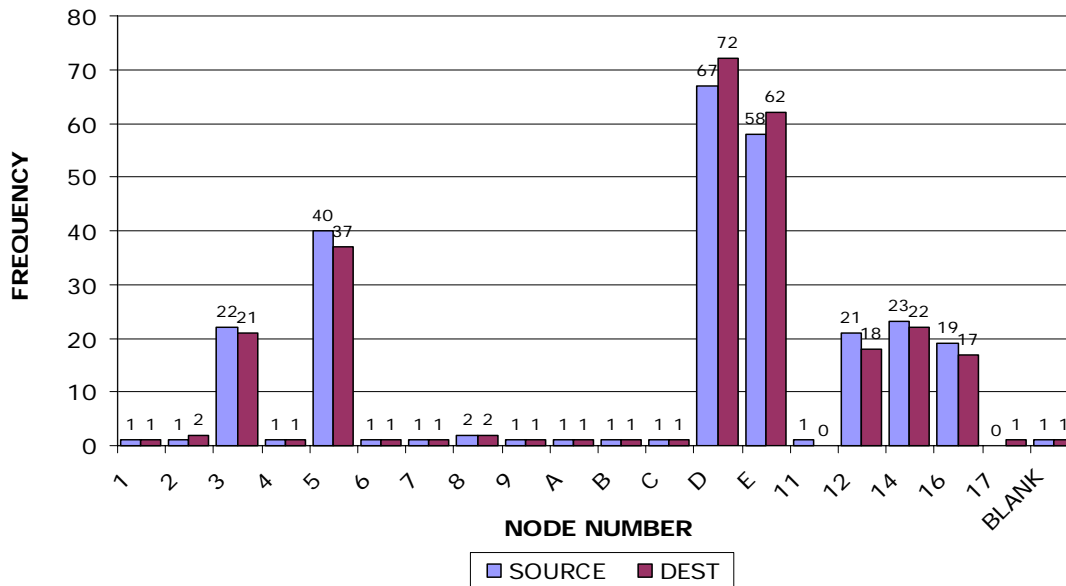
Using the time stamps of the problem packets available in the data set, a comparison could be made to determine where the submarine was at any particular time of transmission, and which node was its intended recipient. This comparison ensured that a fairly accurate determination of whether or not the transmission could be received by the intended node recipient.

## V. FBE-I NETWORK LAYER PERFORMANCE

### A. NODE USAGE

Source addresses are nodes that initiate sending traffic or data packets through the network. G denotes a Gateway node, D a DADs node, and S a Submarine cell. The primary source addresses were nodes GD, GE, D3, D5, and S11-S17.

Destination addresses are nodes that are the final recipient of data packets. The primary destination addresses are once again GD, GE, D3, D5, and S11-S17.



**Figure 5.1 DATA Packet Source & Destination Nodes (Network Layer)**

Figure 5.1 categorizes the network layer source and destination node addresses for the 263 data packets as they were transmitted through the network on June 23. This distribution of source and destination network nodes was expected since nodes GD and GE were the Racom buoy gateways that initiated a majority of the traffic originating at and destined for the ASWCC. Nodes S12, S14, and S16 were the submarine designated operating areas, and were the submarine cells that were mostly utilized. Cells S11 and S17 were located at the turn around for the North and South runs; therefore, these

addresses were not used as often. The submarine was, by design, the intended recipient for much of the experimental traffic. Nodes D3 and D5 were the DADs sensor nodes that initiated contact reports to be transmitted to the ASWCC for further dissemination via the D and E gateways. The various other individual R node usages were most likely the nodes receiving and responding to health/status requests from the ASWCC.

## B. ROUTING TABLES

Each column is the routing table for the modem at the designated node address.

S-Register	R1	R2	D3	R4	D5	R6	R7	R8	R9	RA	RB	RC	GD	GE
41	1	1	2	2	4	B	6	2	8	4	A	9	C	C
42	2	2	2	2	4	B	6	2	8	4	A	9	C	C
43	2	8	3	3	4	B	6	3	3	4	A	9	C	C
44	2	8	9	4	4	B	6	9	4	4	A	9	C	C
45	2	8	4	5	5	B	6	9	4	5	5	A	C	C
46	2	8	4	A	B	6	6	9	4	B	6	A	C	C
47	2	8	4	A	B	7	7	9	4	B	6	A	C	C
48	2	8	4	A	4	B	6	8	4	4	A	9	C	C
49	2	8	9	9	4	B	6	9	9	4	A	9	C	C
4A	2	8	4	A	A	B	6	9	4	A	A	A	C	C
4B	2	8	4	A	B	B	6	9	4	B	B	A	C	C
4C	2	8	9	9	A	B	6	9	C	C	A	C	C	C
4D	2	8	9	9	A	B	6	9	C	C	A	D	C	C
4E	2	8	9	9	A	B	6	9	C	C	A	E	C	C

**Table 2. Routing Tables**

Note that these tables can be modified via acoustic command following deployment of the network. For example, on the last day of the FBE-I test, node RC was taken out of most routes to reduce latency. The routing tables for all modems that used ‘C’ in their route were acoustically reprogrammed to replace ‘C’ to either ‘9’ or ‘A’ for outgoing routes and either ‘D’ or ‘E’ for incoming routes.

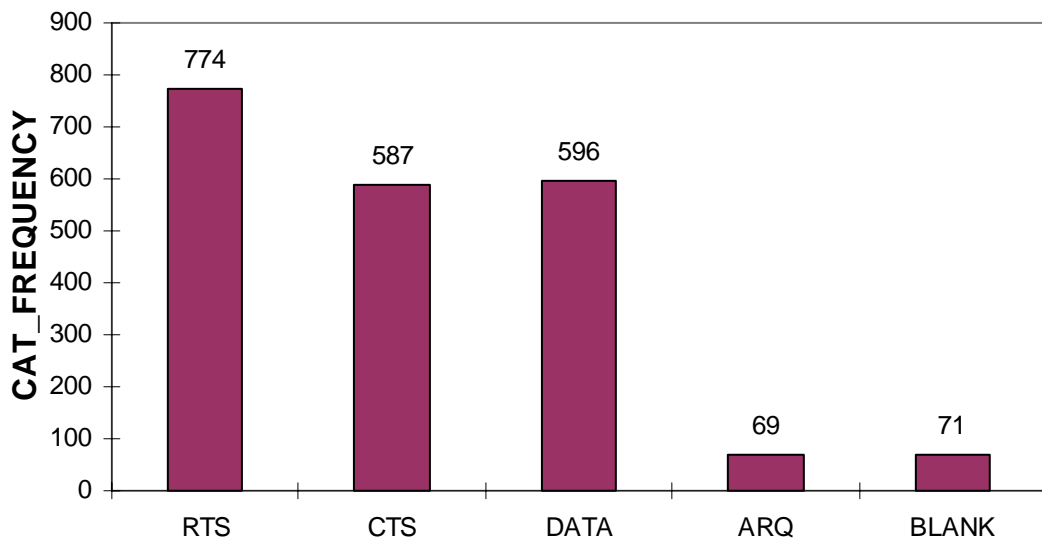
The network identifies four types of packets. During the experiment of 23 June 2001, the network trafficked a total of 2097 packets throughout the system. These 2097 packets were categorized by the traffic sent from source to destination node and mapped (via) their respective routings throughout the Seaweb network nodes. Each of these 2097 elements produced a total of 263 serials.

A serial is described as the source to destination identity of a DATA packet. Each time the DATA packet was sent via the prescribed routing table, it took the form of RTS-CTS-DATA. Associated with the DATA packet is the size of the packet. A link is

described as node-to-node transfer of information. Analysis shows that there were 263 serials at the network layer, and 525 links at the link layer.

### C. PACKET TRAFFIC

Figure 5.2 is a histogram of the packet traffic by packet type throughout the network. The breakdown of the 2097 packets are as follows: there were 774 RTS packets, 587 CTS packets, 596 DATA packets, 69 ARQ packets, and 71 UNK packets



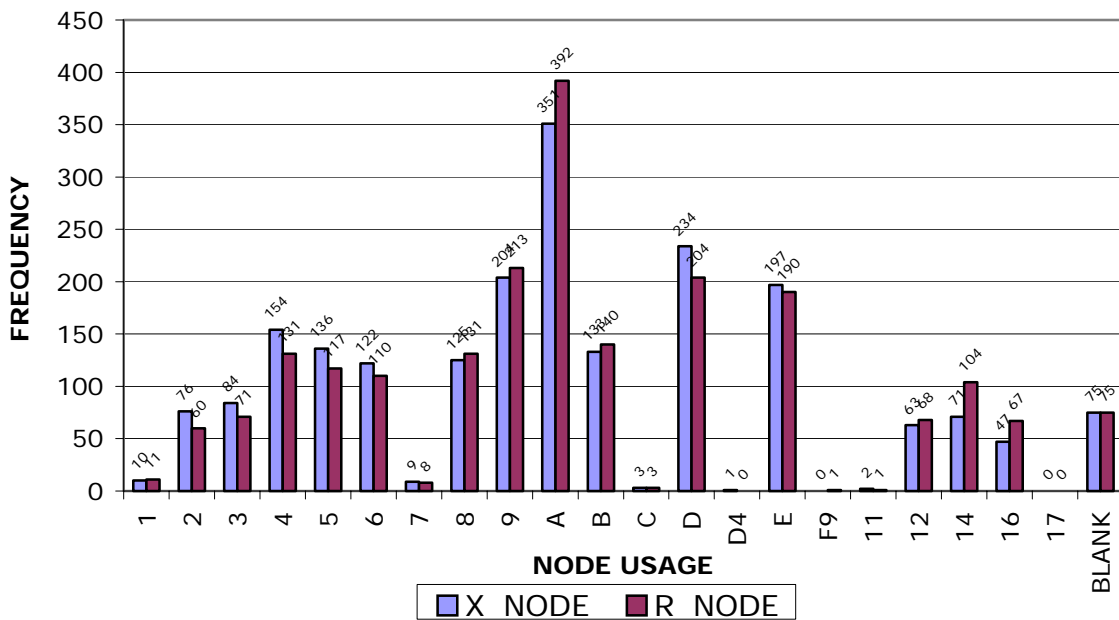
**Figure 5.2 Distribution of Packets Transmitted, by Packet Type**

throughout the network. The network propagates RTS retries (Up to five) after a certain lapse timeframe to ensure the data can be trafficked throughout the network to its intended recipients. This explains the large number of RTS transmissions (RTS retries) in the histogram. UNK'S represent an inability to identify the type of transmission through the analysis means available. Transmissions occurred, but the monitoring gateway could not identify the specific packet type. Keep in mind that the sequencing of data packets is RTS-CTS-DATA, then ARQ-DATA when necessary (up to three ARQ's). Note: Notice the elemental counts do not match. This indicates that some data packets

made their way through the network, even though the monitoring system did not properly log the network activity.

**D. NODE USAGE**

Figure 5.3 tallies the link layer transmitter and receiver node usage for the 2,097 DATA packets occurring in the network. As will be discussed in Figure 5.6, the number of links per data packet was grouped into the network layer statistics. Figure 5.3



Error!  
**Figure 5.3 Node Usage (Link Layer)**

demonstrates the node usage for all individual links from node to node as each DATA packet moved from source to destination. While a packet was transmitted from source to destination, it may have traveled from Gateway Delta (GD) to Sub cell (S14). To complete the transmission it would have traveled from GD to Repeater Node (R9), R9 to R4, then finally from R4 to S14.

Source (GD) to Destination (S14) – One Serial Data packet

GD to R9 – 1<sup>st</sup> Link

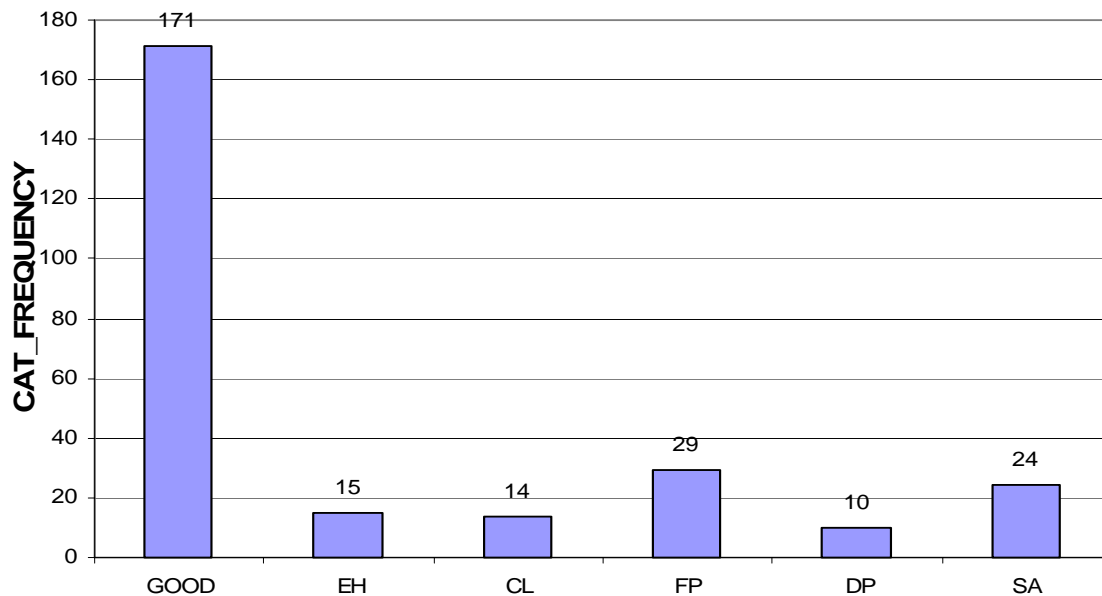
R9 to R4 – 2<sup>nd</sup> Link

### R4 to S14 – 3<sup>rd</sup> Link

This example DATA packet transmission is accounted for in the GD transmit column, R9 Receive column, R9 transmit column, and R4 receive column, R4 transmit column, and the S14 receive column adding one to the total of each column in Figure 5.3 histogram.

The histogram accounts for the total number of links that all DATA packets encountered while traveling through the network to get from source to destination. Note the D4 and F9 node annotations. These nodes were recorded as a result of information contained in the source data. These nodes did not exist within the network. The assumption is those nodes should have been more aptly reported as nodes D and E respectively.

#### E. DATA PACKET OUTCOME



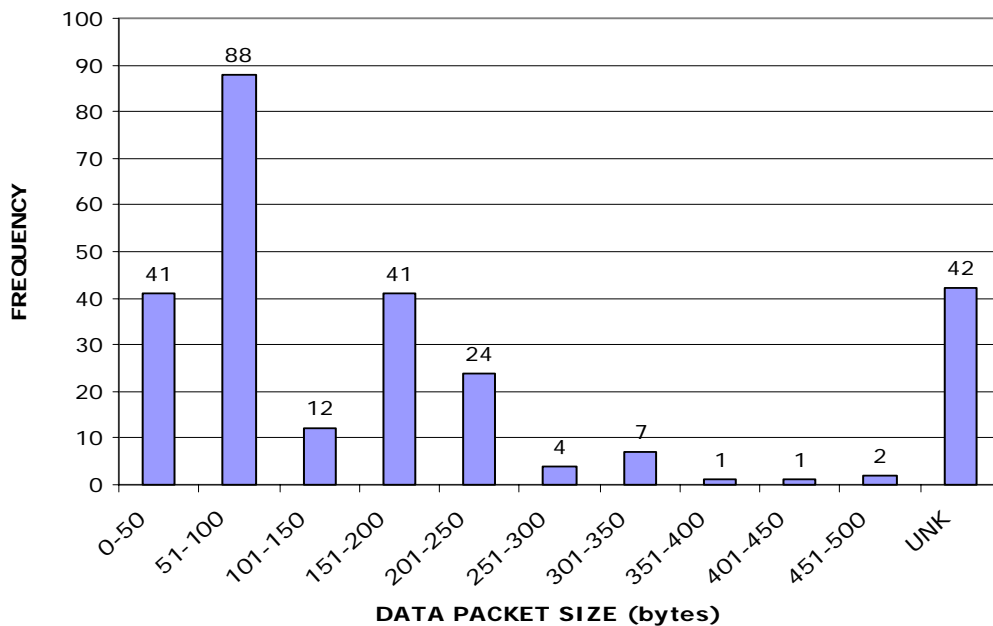
**Figure 5.4 DATA Packet Fates**

Figure 5.4 is a histogram of the fate of DATA packets transmissions throughout the network. There were a total of 263 DATA packets offered to the Seaweb network on

23 Jun 2001. This is the sequencing of DATA transmissions throughout the network from source to destination node inclusive of all the intermittent nodes along the prescribed path of the transmission. The breakdown of the 263 serial packet transmissions are as follows: there were 171 GOOD transmissions, 10 Depth Problem (DP) transmissions, 24 Submarine Aspect (SA) transmissions, 15 Error in Header (EH) transmissions, 14 Collision (CL) transmissions, and 29 Fractional Packets (FP) data packet transmissions throughout the network. GOOD is defined as the successful transmission of DATA packets from source to destination node. DP is defined as a problem encountered by the unsuccessful transmission of a data packet from source to destination node while the submarine was in a depth transition. SA is defined as a problem encountered by the unsuccessful transmission of a data packet from source to destination node while the submarine was attempting to transmit to a node located aft of its beam. EH is defined as a problem encountered by the unsuccessful transmission of a data packet from source to destination node with missing elements of the data packet. CL is defined as a problem encountered by the unsuccessful transmission of a data packet from source to destination node interrupted by another transmission occurring at the same time at a particular node in the serial. FP is defined as a problem encountered by the interruption of a successful transmission of a data packet from source to destination, but the data packet successfully made it to the intended node recipient. An administrative scrub of the submarine data log was needed to verify the data packet success. Because the submarine log could only identify in ZULU time, a true latency for this data packet could not be computed. Both the DP and SA problems encountered appear to be influenced by human error. It appears that the error was either by the operator transmitting to a node physically located aft of its beam or the cone angle of the sonar propagation misaligned with the nodes ability to capture the transmission of the information via the medium (ocean). In reviewing this phenomenon, the need for incorporating the submarines actual location with respect to the timing of nodal traffic is necessary, as considered in Section IV(D), Figure 4.5. Investigation was necessary to verify potential (SA/DP) problems encountered in the network.

## F. DATA PACKET SIZE

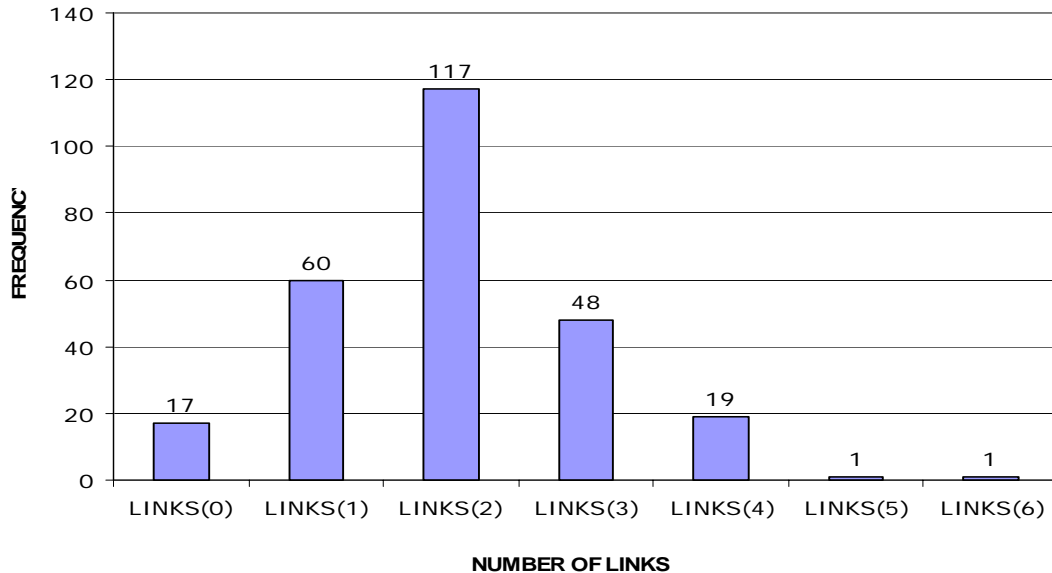
Figure 5.5 categorizes DATA packet size. DATA packet size was categorized in 50 byte intervals. The distribution of the frequency of all 263 packet sizes is accounted for in Figure 5.5. There were 221 data packets with byte size  $\leq 500$ . The remaining 42



**Figure 5.5 Bytes Per Packet**

DATA packets were Unknown (UNK). The DATA packets of byte size UNK were those DATA packets successfully transmitted, but did not have any information about the actual byte size field annotated in the original data set. Of the 42 UNK DATA packets 2 were due to EH problems, 3 to CL problems, 4 to FP problems, 2 to DP problems, 3 to SA problems and 23 to UNK transmission time stamp. In some cases the element type was inferred based on previous transmissions in the network.

## G. LINKS PER DATA PACKET



**Figure 5.6 Number Links per Packet (Network Layer)**

Figure 5.6 demonstrates the network layer number of links per data packet as they were transmitted through the network. While a packet was transmitted from source to destination, it may have traveled from Gateway Delta (GD) to Sub OPAREA (S14). To complete the transmission it would have traveled from GD to Repeater Node (R9), R9 to R4, then finally from R4 to S14.

Source (GD) to Destination (S14) – One Serial Data packet

GD to R9 – 1<sup>st</sup> Link

R9 to R4 – 2<sup>nd</sup> Link

R4 to S14 – 3<sup>rd</sup> Link

This example data packet transmission would have been accounted for in the LINKS (3) category of the Figure 5.6 histogram.

The histogram tallies the total number of links each DATA packet traveled to get from source to destination.

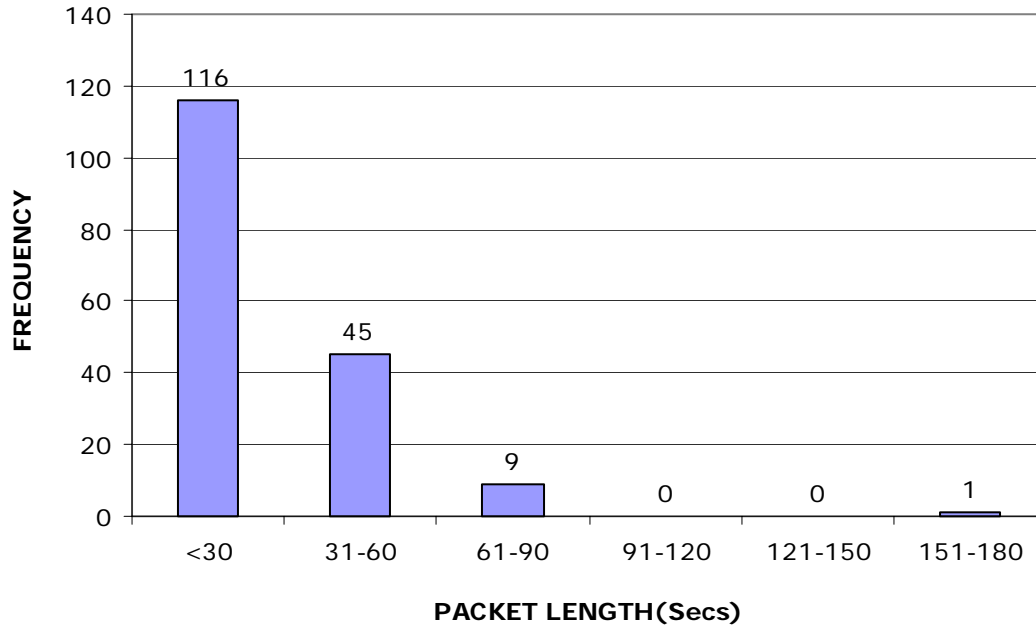
Entry	Serial#	Source	Dest	Problem Area	Notes/Comments
339	55	E	5	CL	COLLISION
467	72			SA	ASSUME RTS 14-9 LOST SUB ASPECT
610	94	D	14	SA	SUB ASPECT
666	100	5	E	CL	COLLISION DATA PACKET SURVIVED
695	103	5	E		ROGUE RTS
735	107	14	D	DP	SHALLOW
738	108	14	D	DP	SHALLOW
759	110	D	14	FP	FRACTIONAL PACKET
799	115	12	D	DP	DEPTH ISSUE
946	134	14	D	SA	SUB ASPECT
964	136	D	14		MISSING CTS DID NOT MEET CRITERIA FOR SERIALIZED PACKET
1206	161	16	D	EH	ERROR IN HEADER SURVIVED
1298	170	5	E	EH	ERROR IN HEADER COLLISIONS
1391	185	12	2	SA	SUB ASPECT
1533	199	D	12	CL	COLLISION
1610	209	E	3	CL	COLLISION
1966	244	D	14	SA	

**Table 3. LINK (0) Explanation**

Explanation for LINKS(0): Previous table describes problem area.

## H. PACKET LATENCY

Figure 5.7 groups the Data packet latency (in Seconds) that each transmission experienced traveling through the network. The histogram accounts for the time one data packet serial takes (in seconds) to get from source to destination node. Data packet



**Figure 5.7 Latency (Network Layer)**

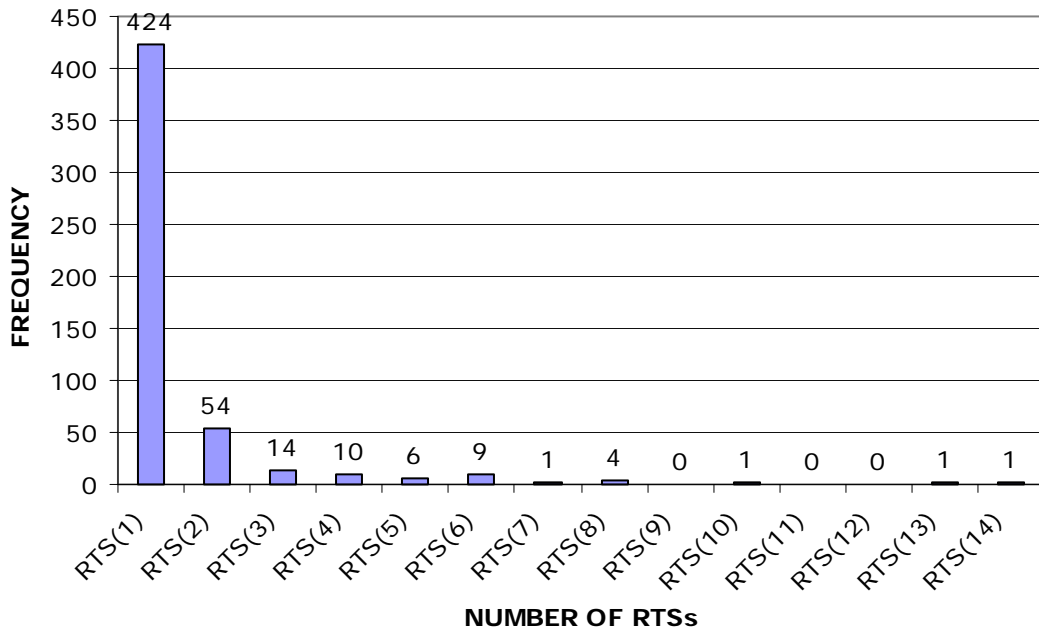
length was categorized in 30 second intervals. This was the total accounting of all 171 GOOD data packets.

Note: Reason for long latency (151-180) - Packet #232 was a depth issue that the data packet survived after a collision with data packet #233.

## VI. FBE-INDIA LINK-LAYER PERFORMANCE

### A. RTS FREQUENCY

Figure 6.1 demonstrates the link layer RTS re-tries that occurred during FBE-I, 23 June 2001. An RTS transmission is sent by the transmitter node to the intended receiver node. The RTS transmission starts the handshaking process at the beginning of each link



**Figure 6.1 RTS Usage (Link Layer)**

until the data packet is received at the intended destination node. The transmitter node issue an RTS retry after a certain lapsed time-frame to ensure the data can be trafficked throughout the network to its intended recipients.

During FBE-I, a maximum number of RTS transmission attempts were set at 5. Once 5 attempts were completed, the data packet was programmed to cease transmission, and the DATA packet would be dropped. The figure shows that the majority of the RTS transmissions were successful on the first attempt (424 out of 774). 54 after the two, 14 after three, 10 after 4, and 6 were successful after 5 attempts.

RTS(1 attempt) = 424

RTS(2 attempts) = 54

RTS(3 attempts) = 14

RTS(4 attempts) = 10

RTS(5 attempts) = 6

Total:  $424 \times 1 + 54 \times 2 + 14 \times 3 + 10 \times 4 + 6 \times 5 =$

$424 + 108 + 42 + 40 + 30 = 644$

644 out of 774 were successful within the allotted 5 RTS retry attempts.

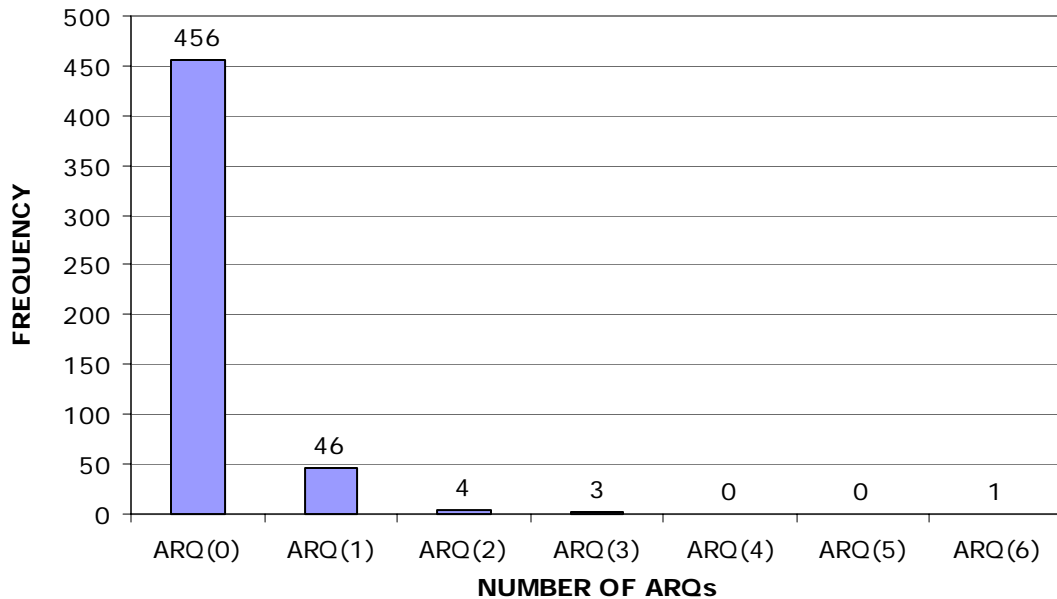
RTS_Count	Pckt#	Link#	Problem Area
6	134	256	SA
6	138	263	SA
6	151	288	DP
6	152	289	DP
6	153	290	DP
6	154	293	SA
6	185	345	SA
6	186	348	SA
6	239	478	SA
7	162	307	SA
8	55	110	CL
8	104	199	R-RTS
8	115	220	DP
8	243	486	CL
10	140	266	SA
13	94	180	SA
14	106	206	DP

**Table 4. RTS>5 Overage Count Explanation**

TABLE 4 gives explanation for those communications overheard by the network that were in excess of the set limitation on the number of RTSs for the experiment.

## **B. ARQ FREQUENCY**

Figure 6.2 demonstrates the link layer ARQ attempts/re-tries that occurred during FBE-I, 23 June 2001. Automatic Repeat Request (negative acknowledgement); 525 ARQ transmissions occurred. An ARQ transmission is sent by the intended receiver node to the transmitter node originating the DATA packet. The ARQ transmission



**Figure 6.2 ARQ Usage (Link Layer)**

indicates to the transmitting node that the data packet was not received at the intended recipient/destination node, or that it was received with uncorrectable errors. The initial transmitting node would then re-transmit the DATA packet. The node issues an ARQ re-try after a certain lapsed time-frame; however, during FBE-I, a maximum number of ARQ transmission attempts were set at 3. Once 3 attempts were completed, the data packet was programmed to stop trying, and the DATA packet would be dropped. The figure shows that the majority of the transmissions were successful without ever having to utilize the ARQ process (456 out of 525). 46 after the first, 4 after the second, and 3 were successful after the third ARQ attempt.

$$\text{ARQ (0 attempts)} = 456$$

$$\text{ARQ (1 attempt)} = 46$$

$$\text{ARQ (2 attempts)} = 4$$

$$\text{ARQ (3 attempts)} = 3$$

$$\text{ARQ (6 attempts)} = 1$$

$$\text{Total: } 456 + 46 \times 1 + 4 \times 2 + 3 \times 3 + 6 \times 1 =$$

$$456 + 46 + 8 + 9 + 6 = 525$$

519 out of 525 were successful within the allotted 3 ARQ attempts.

The figure also demonstrates even though the ARQ limitation was set at 3, link number 266, packet number 140 established 6 ARQs to attempt to complete its transmission through the network. The reason for the excess number of ARQ attempts was caused by a submarine aspect problem during the attempted transmission.

## VII. CONCLUSION

This thesis presents statistical analysis of the FBE-I Seaweb link-layer and network-layer performance on 23 June 2001. The results show that Seaweb is a viable technology for internetworking various undersea, surface, and airborne resources.

This analysis was limited to observations obtained largely from gateway GD operating as a system monitor. The inability of GD to monitor some traffic caused some holes in the analysis. This could be remedied through the implementation of a distributed monitoring capability, where each node logs diagnostics about traffic it is involved in.

Further analysis would benefit from the availability of a Seaweb simulator representing the network layer and link layer. This would provide a design tool for studying the deterministic and probabilistic nature of the network. It would also assist in defining or redefining certain operational aspects of the network with respect to its performance measures (i.e. quality of service, latency, throughput, and reliability).

This thesis demonstrates that the Seaweb network technology performed reliably and has great potential for transforming the nature of undersea warfare. Underwater sensor fields and wireless communication network will most likely be the answer to homeland protection and power projection abroad to deter hostile actions against U.S. allies and interests.

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